The Challenge and Excitement of Space Robotics

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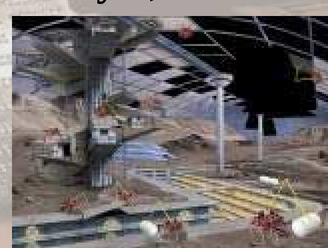

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Outline

- **Does Space + Robotics = "Space Robotics"?**
- **Robotic Exploration and In-Space Operations**
- **Teleoperation and Supervised Autonomy**
- **Experimental Examples: Teleoperation (robotics)**
- **Experimental Examples: Supervised Autonomy**
- **Making Robots Smarter: "On-board Intelligence"**
- **Toward Future "Networked Robotic" Systems**
- **The Space Vision: Moon, Mars, and Beyond**

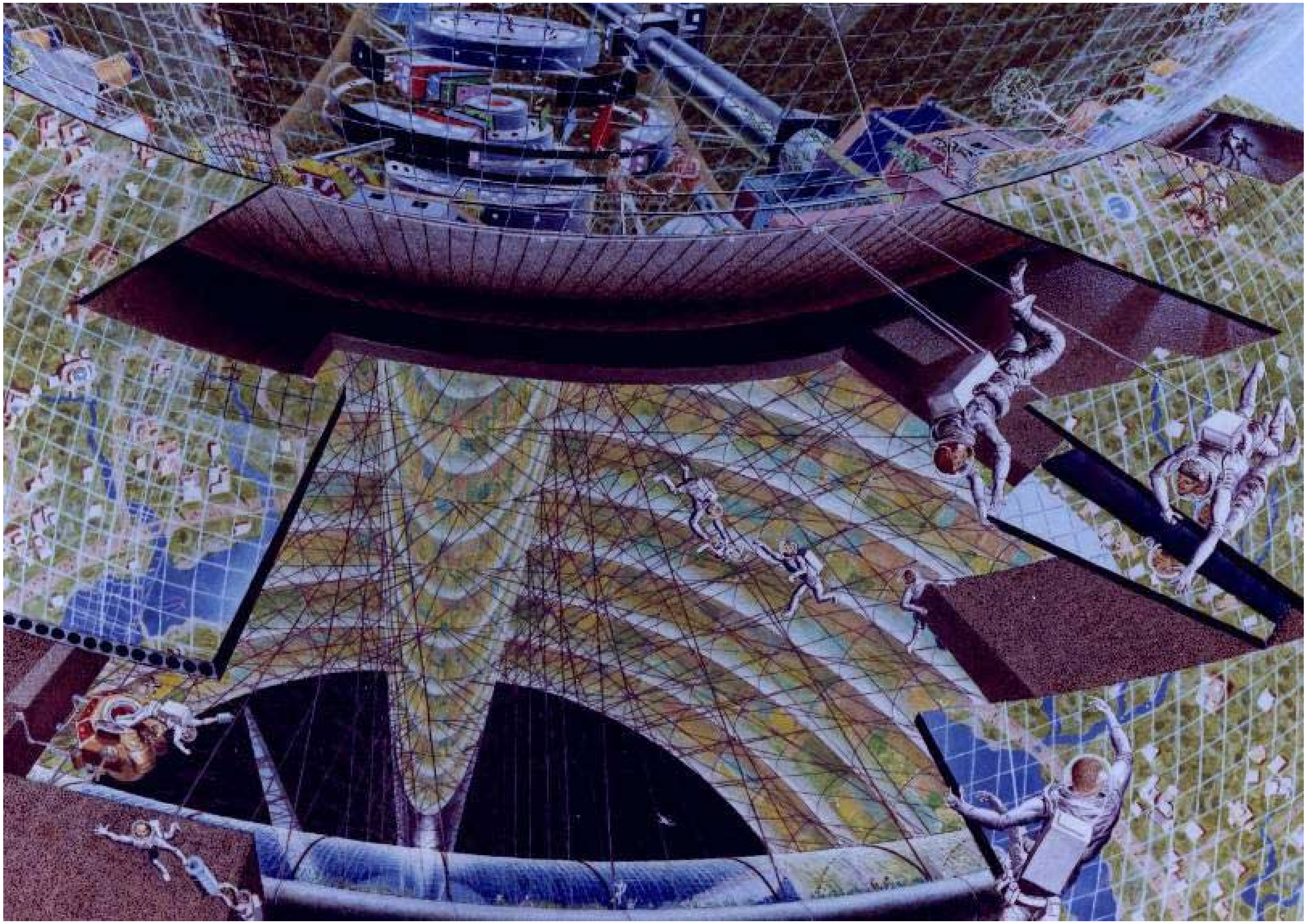
“Space”

- **Empty, a vacuum …**
- **Low or no gravity …**
- **Cold, hot, variable …**
- **Other atmospheres …**
- **Turbulent, windy …**
- **Hard, soft surfaces …**
- **Smooth, sandy, rocky …**
- **Extreme, challenging terrain …**
- **<u>Far away from us in time, distance …</u>**
- **<u>Unknown, unpredictable, harsh environments …</u>**

"Robotics"

- **Senses, detects …**
- **Moves, manipulates …**
- **Mechanical, electrical …**
- **"Joysticked" controller …**
- **Pre-scripted set of actions …**
- **Dumb, dirty, repetitive work …**
- **Not self-aware, limited knowledge …**
- **<u>Fixed skills, inflexible configuration …</u>**
- **<u>Lacking in human qualities or "social" skills …</u>**

Space Robotics (~1970!)

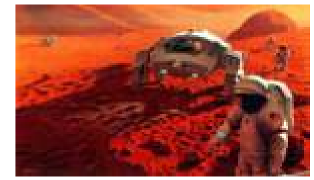


Space Robotics

- **Engineering**: robotics, in the NASA operations context, is a surrogate for, or enhances and extends the presence of human mobility, manipulation, and intelligence in space
  - Putting these capabilities where humans cannot yet go, in order to carry out human-like endeavors, e.g., Mars field geology and precursor studies of resources/habitability
  - Putting these capabilities where humans can go, for reasons of task complexity, scale, duration, and human/robot system safety
  - Extending human "reach" to the space frontier from Earth, e.g., through tele-presence and telerobotic ground support
  - Working along-side humans in durable habitat construction and maintenance, etc.
- **Science**: robotics enables improved access to critical data and breakthrough measurements within the solar system—or the human/robotic partnered creation of new in-space science facilities to do the same
  - Diverse instrument placements on planetary and lunar surfaces
  - Mobility to high-risk/high-payoff science sites such as Mars cratered slopes
  - Autonomous aerial survey of planetary, lunar and small bodies
  - Subsurface drilling/melting into pristine historical science records
  - Precursors for *in situ* resource analysis leading to safe, durable habitation
  - Human/robot work crews that emplace science observatories/bases

Desired Space Robotics Capabilities

- **Solar System Exploration**

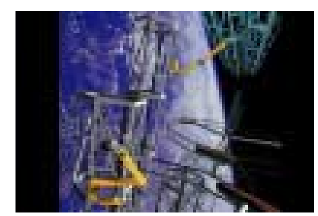


  - **Autonomous mobility and access (surface, aerial, and sub-surface)**
  - **Autonomous instrument deployment (from landed and mobile platforms)**
  - **On-board autonomous science (with applications to opportunistic exploration)**
  - **Human-robotic field science (robotic scouts, assistants, telepresence, multi-robot cooperation)**
  - **Human-robot interaction (remote and on-site C^4I for mission planning, operations, monitoring)**

- **Lunar & Planetary Habitation**

  - **Site development (survey, excavation, initial construction, resource deployments)**
  - **Site maintenance (inspection, repair, assembly, materials transport & warehousing)**
  - **In situ resource production (robotic support to extraction, transport, manufacturing)**
  - **Field logistics and operations support (materials & equipment transport & warehousing)**
  - **Human-robot interaction (H/R task allocation, teleoperation, remote supervisory control, etc.**

- **Robotics for In Space Operations**

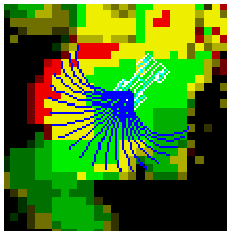


  - **Assembly (manipulation, preparation, connecting, self-deployment)**
  - **Inspection (structural, access, component/system failure detection)**
  - **Maintenance (staging, H/R interface rated manipulation, grapple dexterity)**
  - **Human-robot interaction (multi-agent teams, communication of intent, time delay compensation)**

Planetary Science

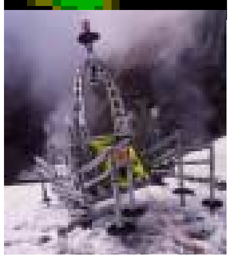
(Reference: NExT Study on Space Robotic Capabilities)

Mobility (Surface and More)



Mobile Autonomy

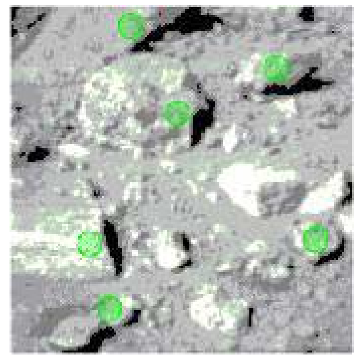
Terrain assessment, path planning, visual servoing



Mobility Mechanization

Extreme terrain access, energy efficiency

Science Perception, Planning & Execution



On-board and ground tools; data analysis, target selection, operations planning and execution

Human-Robot Interactions

"Scaleable" teleoperative and telerobotic control of remote explorers

Robotic work crews with integral human activity

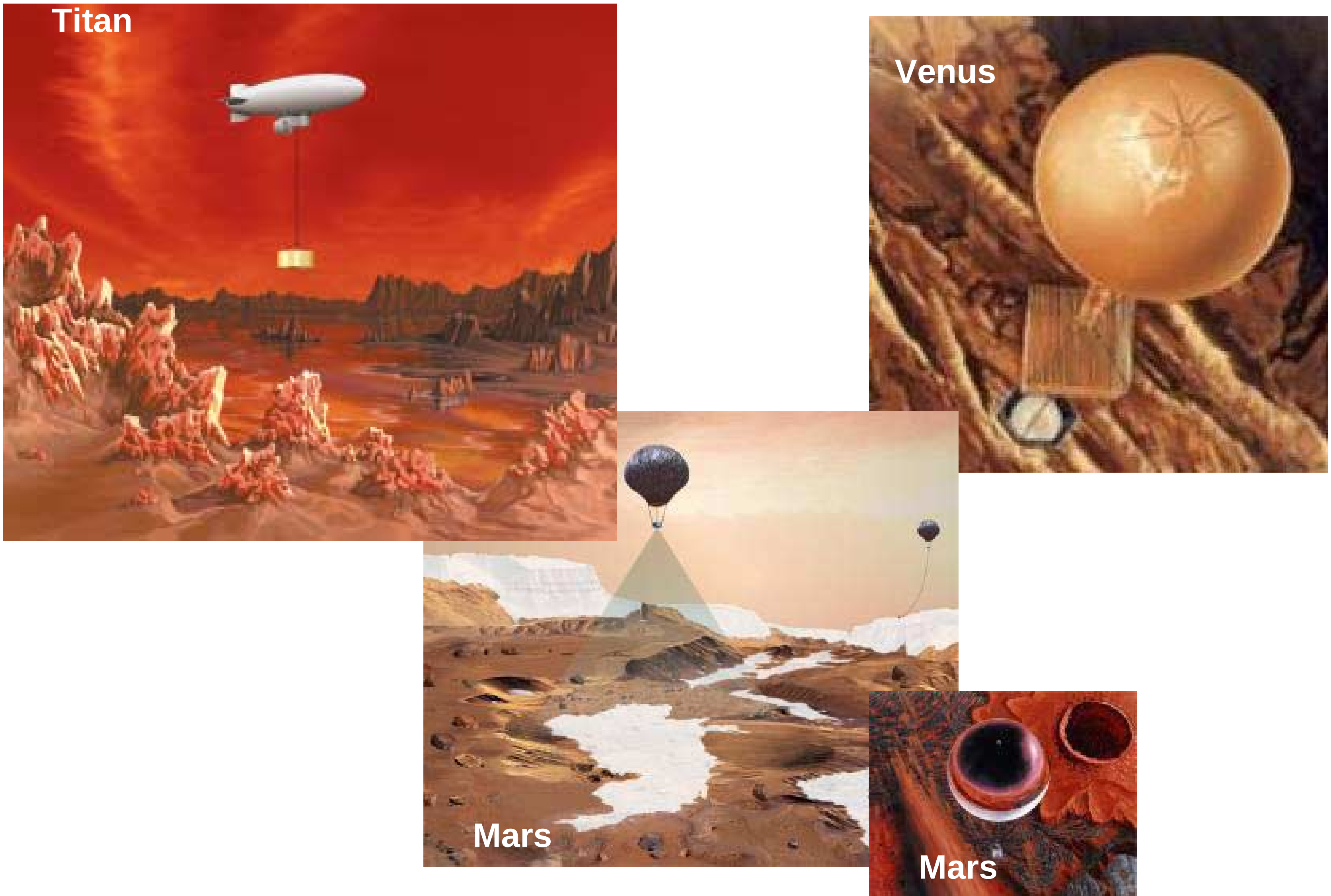
Instrument Placement and Sample Manipulation

Precision placement of sensors, collection and processing of samples

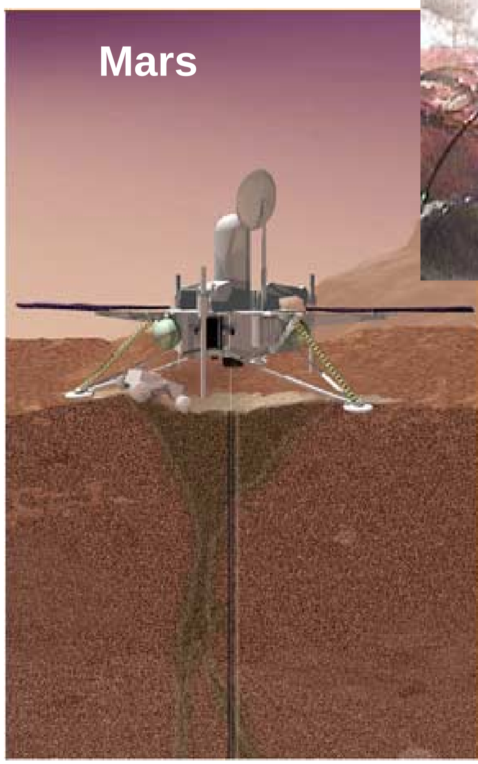
Example: Planetary Surface Science

"Keystone" on the "Methuselah" outcrop of layered rock on "Husband Hill" inside Mars' Gusev Crater (from Spirit's 469th Martian day, or "sol", April 28, 2005).

Aerial Exploration



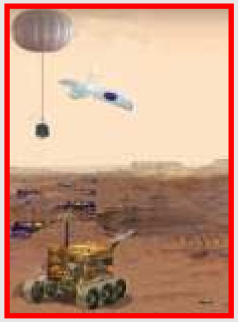
Subsurface Exploration



Solar System Exploration Future Challenges

Space Science and Operational Goals

- **Extend the range and duration of single missions**
- **Reduce uplink cycles per science target acquisition**
- **Enhance diversity of instrument deployment options**
- **Provide mobile access to more featured, adverse terrain**



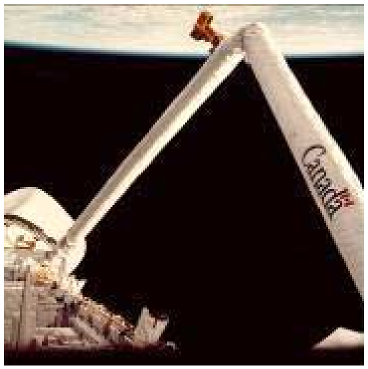
- **Broaden surface payload landing options (hard and soft)**
- **Access disparate subsurface regions (soil/rock, ice/water)**
- **Span highly variable atmospheres (controlled ascent/descent)**
- **Return pristine surface & subsurface samples for earth analysis**

- **Coordinate aerial, surface, & subsurface assets for global coverage**
- **Increase fidelity of ground simulation, operations & science training**
- **Sustain—ultimately—a permanent networked robotic science presence …**
- **…and implement a meaningful partnership between humans & robots in space.**

In-Space Operations

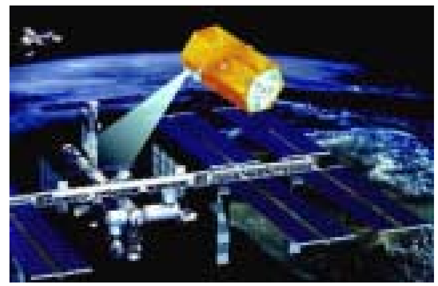
(Reference: NExT Study on Space Robotic Capabilities)

Assembly



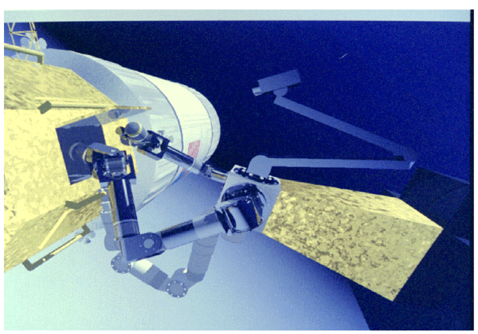
Transporting and mating of components; making connections; assembly sequence planning and execution; assembling small structures

Inspection



Visual inspection of exterior spacecraft surfaces; path planning and coverage planning; automated anomaly detection

Maintenance

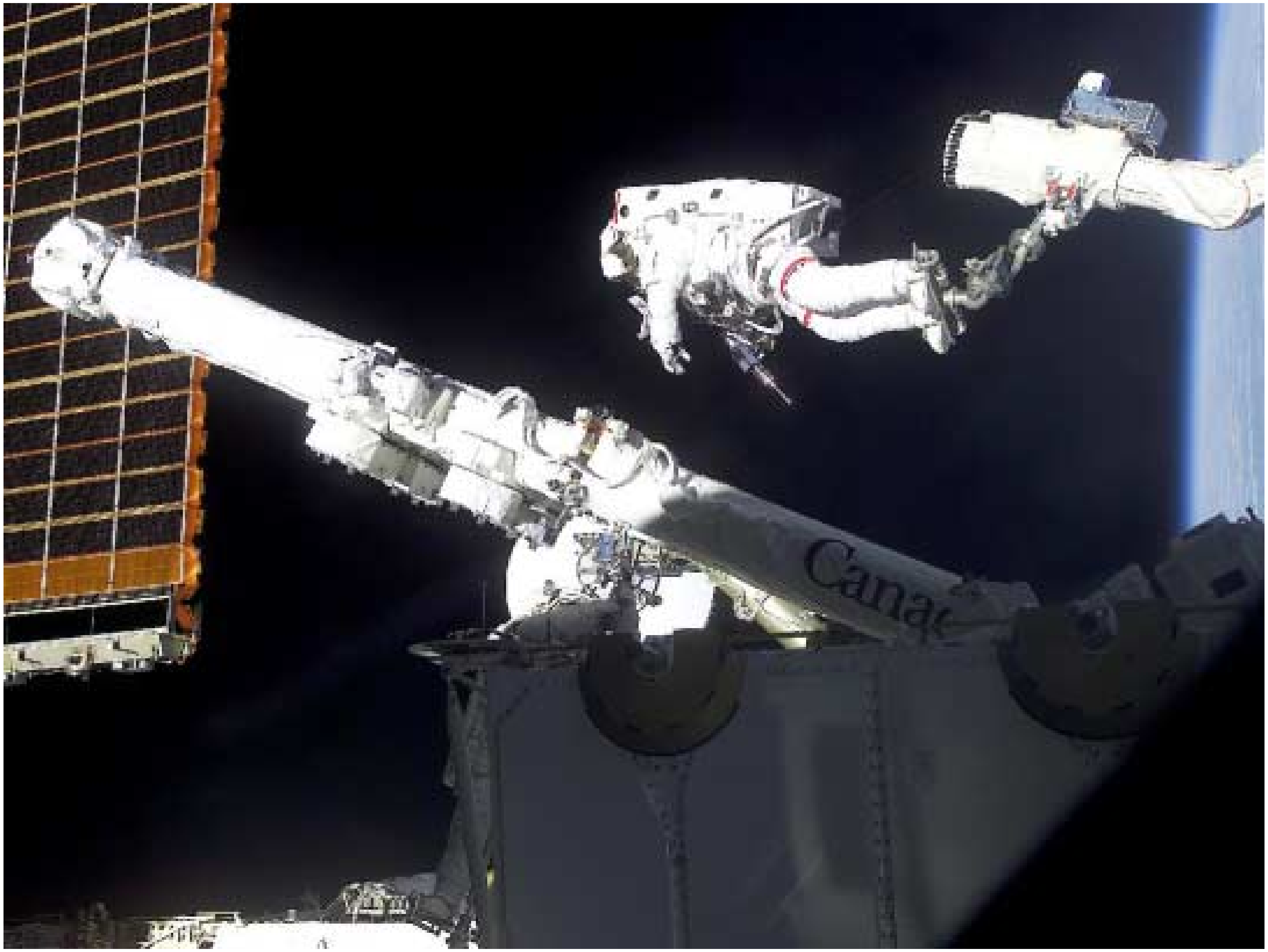


Access to and change-out of components; robotic refueling; structural repair and modification

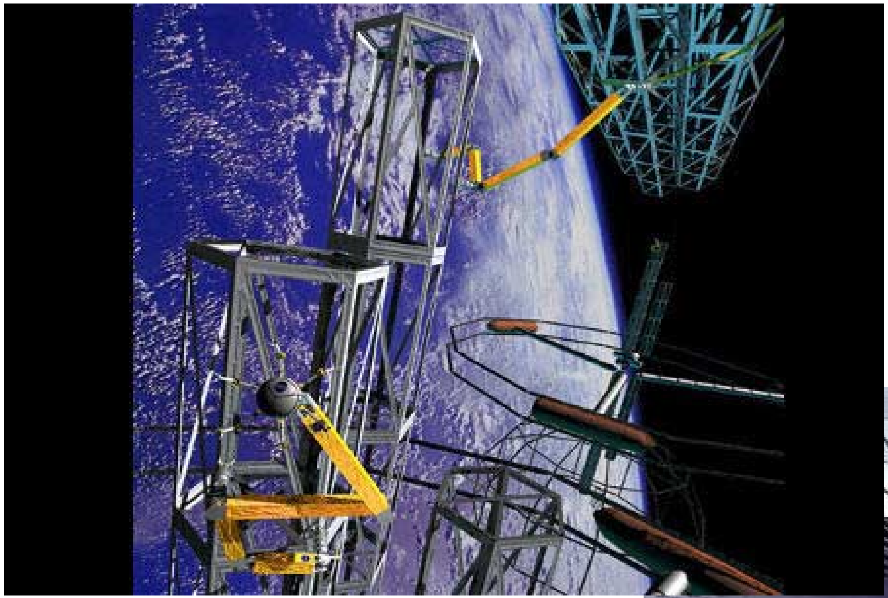
Human EVA Interaction

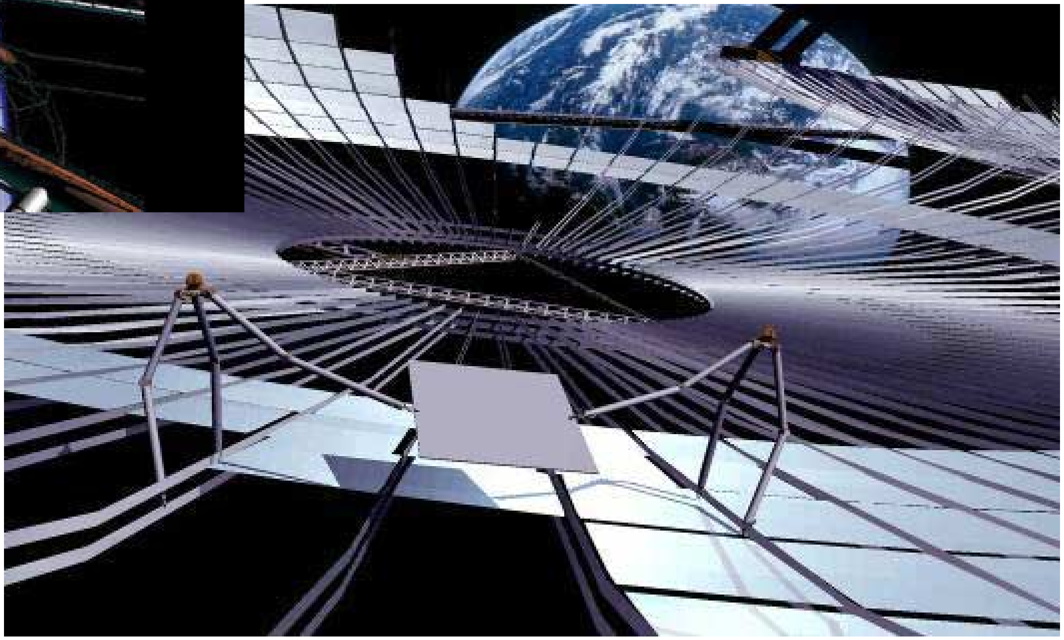
Monitoring / documenting EVA tasks; preparing a worksite; interacting with astronauts; human-robot teaming

Example: In-Space Operations



In Space Assembly





Characteristics of Space Robotic Systems

Two Different Aspects of Space Robotics

Teleoperation

- Structured, often well-modeled, sometimes cooperative environment
- Low latency or none, but past 250 msec, a new operational regime
- Global viewing is limited, can be obscured, low fidelity is an issue
- Sensory feedback often multi-modal and non-intuitive to operator
- Secondary workload is an issue, may require multiple operators
- Dexterity, haptics, human-rated performance of interest (metrics?)
- Evolution of teleoperation to ***telerobotic*** shared and traded control
- Signal-Sign-Symbol, "Visually Servoed-Guided-Designated", etc.

Supervised Autonomy

- Unstructured, partially-modeled, rarely a "cooperative" environment
- High latency, structured planning/CDH, limited contingency handling
- Limited mass, volume, power, and communication; compute bound
- Localized perception and situational awareness primary to s/c safety
- Mid-range localization/servoing and analog planning key to efficiency
- Long range localization and global coordination a key to networking

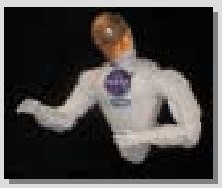
Future Mission Trends for H-R Systems

Space operations will grow in scale; robotic systems will grow in complexity

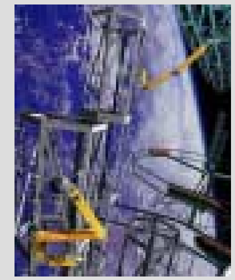
SOLAR SYSTEM EXPLORATION
- Explore large aerial, surface, and sub-surface regions
- Precision placement & deployment of instruments
- In-situ drilling, coring manipulation, and processing
- Sustained autonomous operations & resource mgmt
- Cooperative robotic & human/robot task execution

ASSEMBLY, INSPECTION, MAINTENANCE
- Fast, structure-attached crawling
- Handling of small parts, flexible films
- Deploy & adjust delicate optical elements
- Heavy-duty work from unstable bases
- Material acquisition, transport, deployment

Robonaut

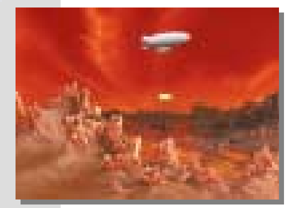


In-Space Assembly



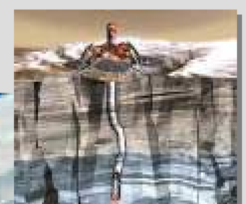
Robot Work Crew

Titan Aerobot



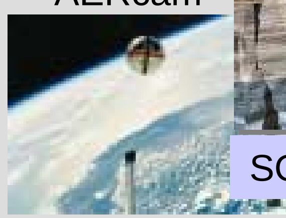
SSRMS (2000)

Mars Drill



MER (2003)

AERcam



SRMS (1985)

SOJOURNER (1997)

Flight Operational Systems

Mobile / Manipulative Degrees of Freedom: 10, 100

Robot Range or Operational Workspace (meters extent): 1, 10, 100, 1000

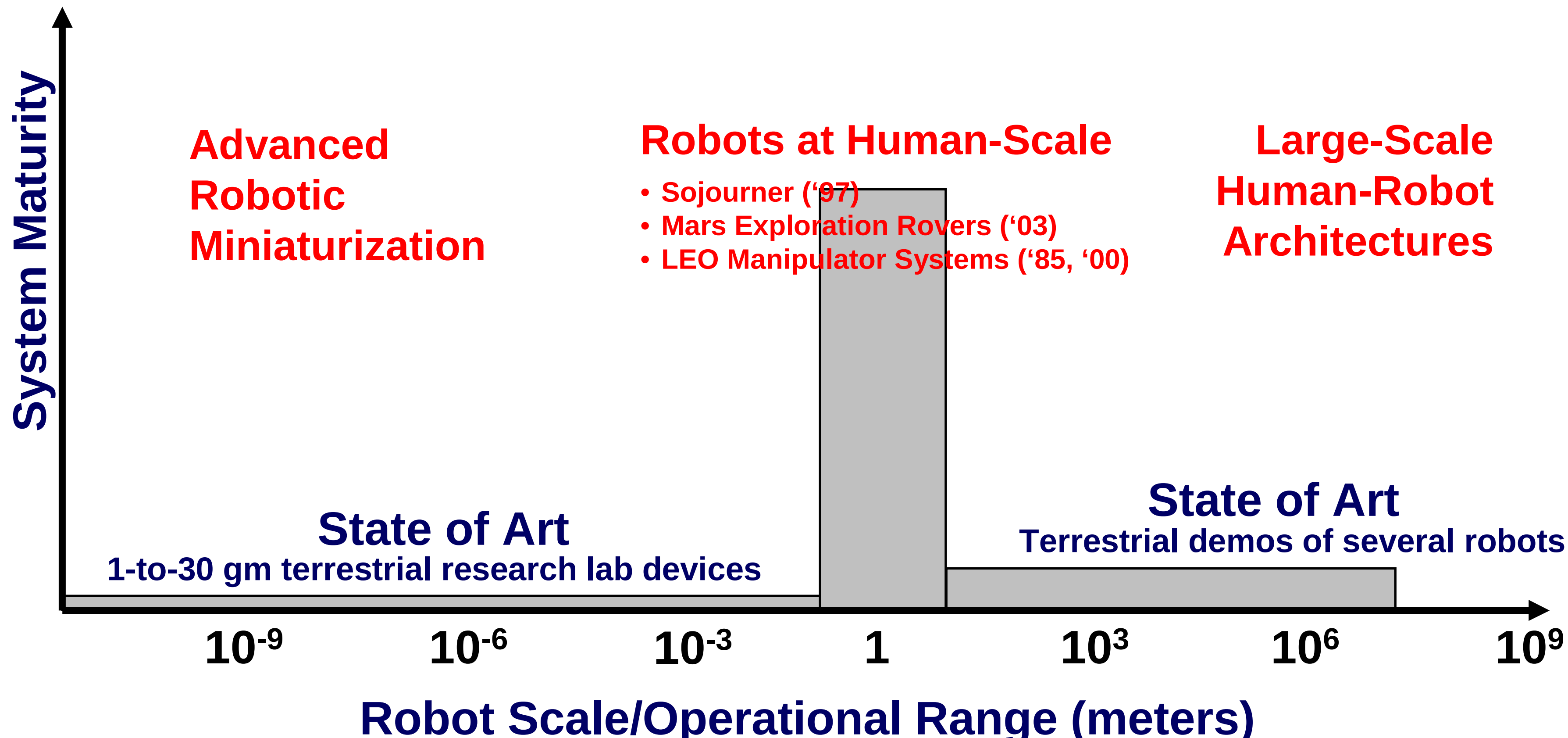
The Scale and Maturation of Space Robotics

"There's plenty of room at the bottom" … and the top

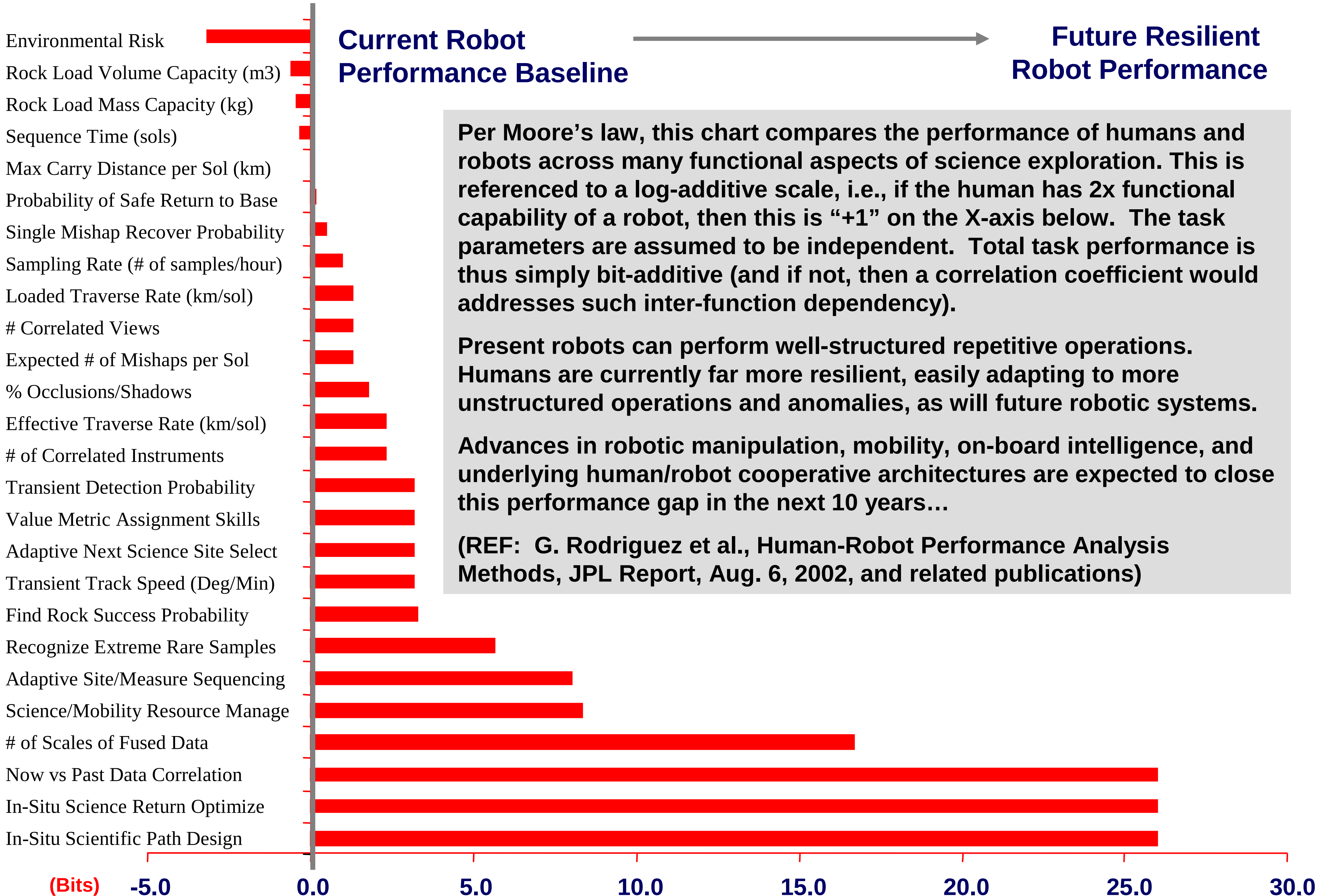
- Nanorover networks
- Mobile local-area nets
- Nano-explorers/workers
- Molecular robots

- Long range navigation
- Sampling mechanisms
- Soft and hard rock coring
- ~10 m subsurface explorers
- In-Space Manipulators

- Global area networks
- Deep subsurface exploration (km)
- Flyers, rovers, subsurface robots
- On-orbit H-R work crews
- Sustained planetary operations
- Modular re-deployable systems



Human & Robotic Performance Comparison



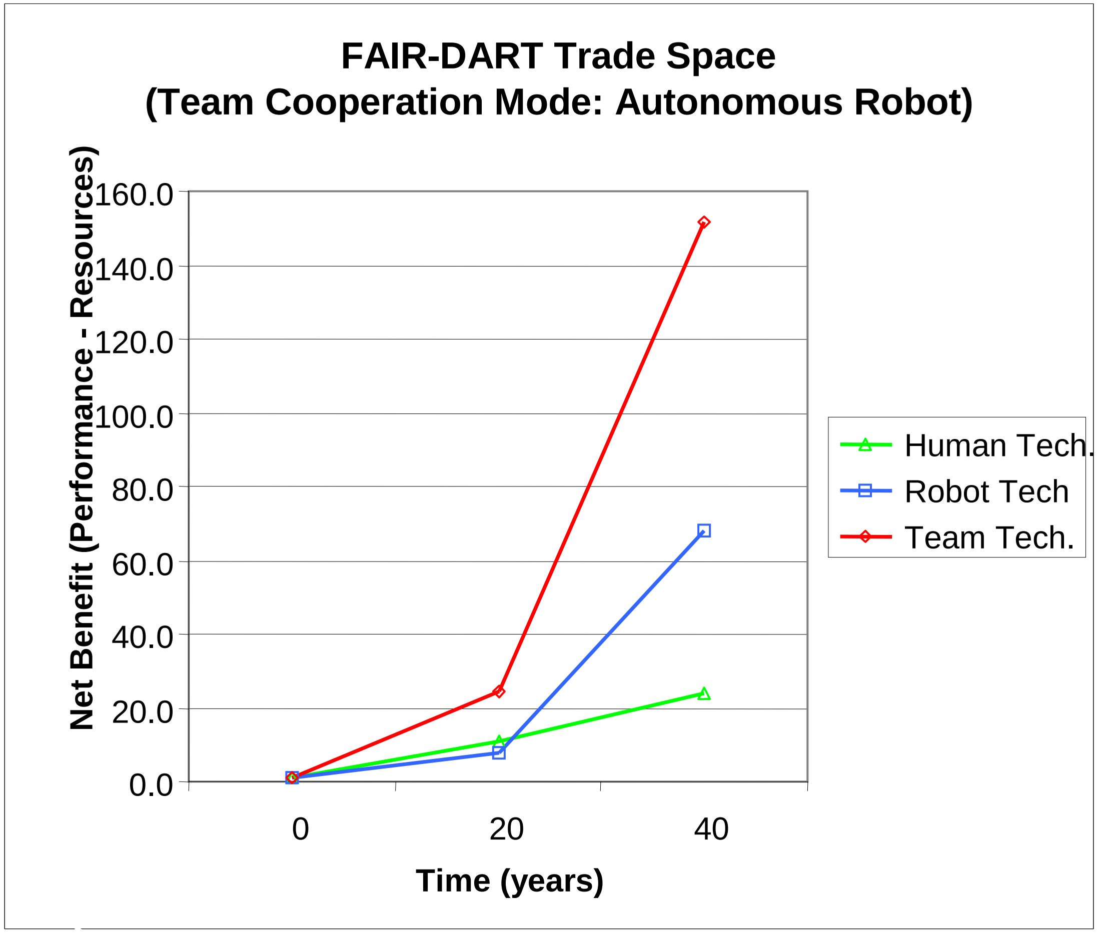
Per Moore's law, this chart compares the performance of humans and robots across many functional aspects of science exploration. This is referenced to a log-additive scale, i.e., if the human has 2x functional capability of a robot, then this is "+1" on the X-axis below. The task parameters are assumed to be independent. Total task performance is thus simply bit-additive (and if not, then a correlation coefficient would addresses such inter-function dependency).

Present robots can perform well-structured repetitive operations. Humans are currently far more resilient, easily adapting to more unstructured operations and anomalies, as will future robotic systems.

Advances in robotic manipulation, mobility, on-board intelligence, and underlying human/robot cooperative architectures are expected to close this performance gap in the next 10 years…

(REF: G. Rodriguez et al., Human-Robot Performance Analysis Methods, JPL Report, Aug. 6, 2002, and related publications)

It's not "Either-Or" Regarding Humans and Robots



Human-Robot Cooperation Improves ROI

This study of L1 orbit telescope assembly demonstrates the potential of human-robot in-space operations to improve NASA ROI as compared to use of either mode alone.

Moore's Law at Work

Y-axis shows projected improvements in EVA and autonomous robotic performance over time. Projected performance has been characterized with respect to numerous task parameters and estimated human versus robotic capability for each. E.g., for a given task parameter, if the human has twice the functional capability of a robot, then this is "+1 bit" on log-2 scale. Task parameters are assumed to be independent, and total task performance is simply bit-additive (and if not, then a model correlation coefficient addresses such inter-function dependency).

NOTE: the result shown here does not assert that EVA is less capable than robotic servicing. Rather, it is shown that projected EVA/technology advances lead to a highly *synergistic human-robotic partnership, one far more productive than results obtainable from human or robotic operations alone*…

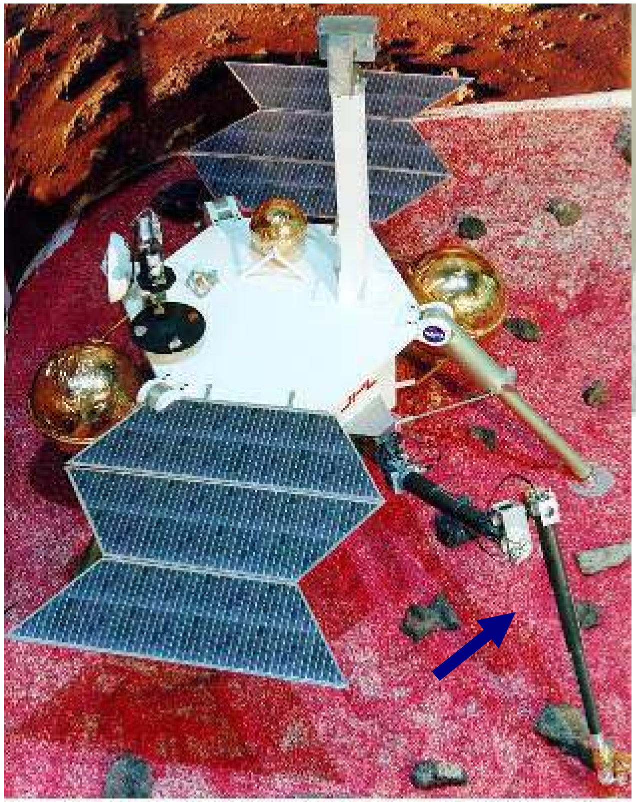
(The initial Condition at 0 Years does not reflect current differences in Human vs Robot Technologies; an estimate of Human EVA of ~20 bits has been obtained from prior studies. The plot for Human technology would have to be displaced upward by this amount in order to reflect such an estimate. Reference: Rodriguez, et al, Human-Robot Performance Analysis Methods, JPL Report, Aug. 6, 2002.)

Teleoperation (Telerobotics) Examples

Fixed and Mobile Manipulation

Teleoperative, telerobotic, and autonomous manipulation technology for:

- ***surface science*** **(instrument placement, sample processing & handling)**
- ***on-orbit operations*** **(assembly, inspection, servicing) and**
- ***commercialization*** **(medical applications of robotics, etc.)**



Above: Dual Arm Surgical Tele-Manipulator (RAMS)

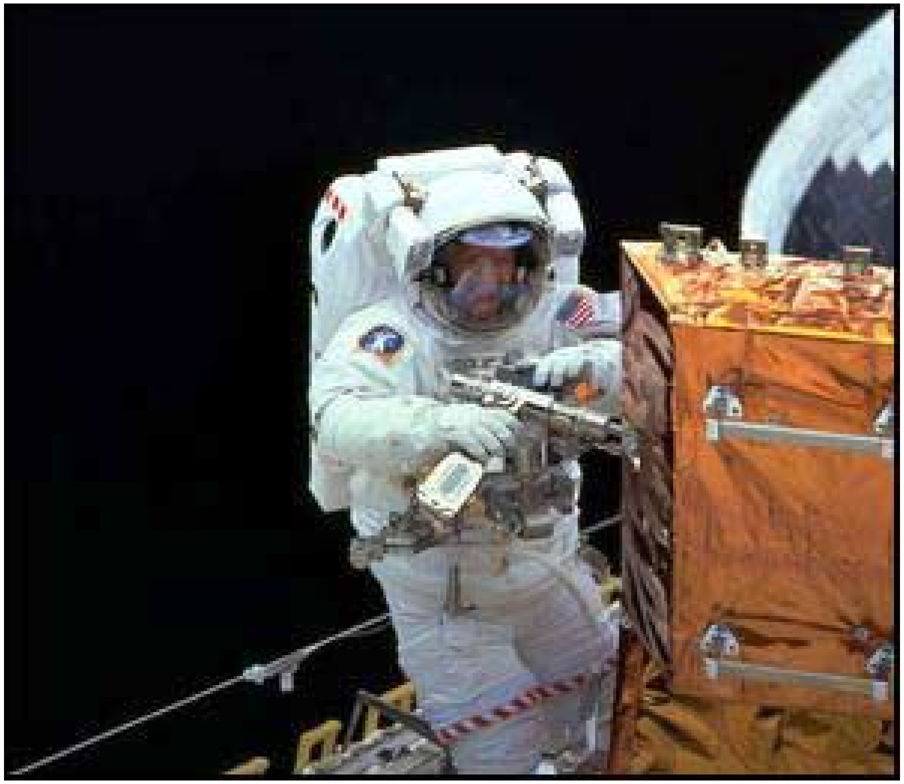
Left: Lander-Manipulator with Camera (Phoenix)

Right: Mobile Instrument Placement (MER)

Example: Medical Robot Extends Human Dexterity

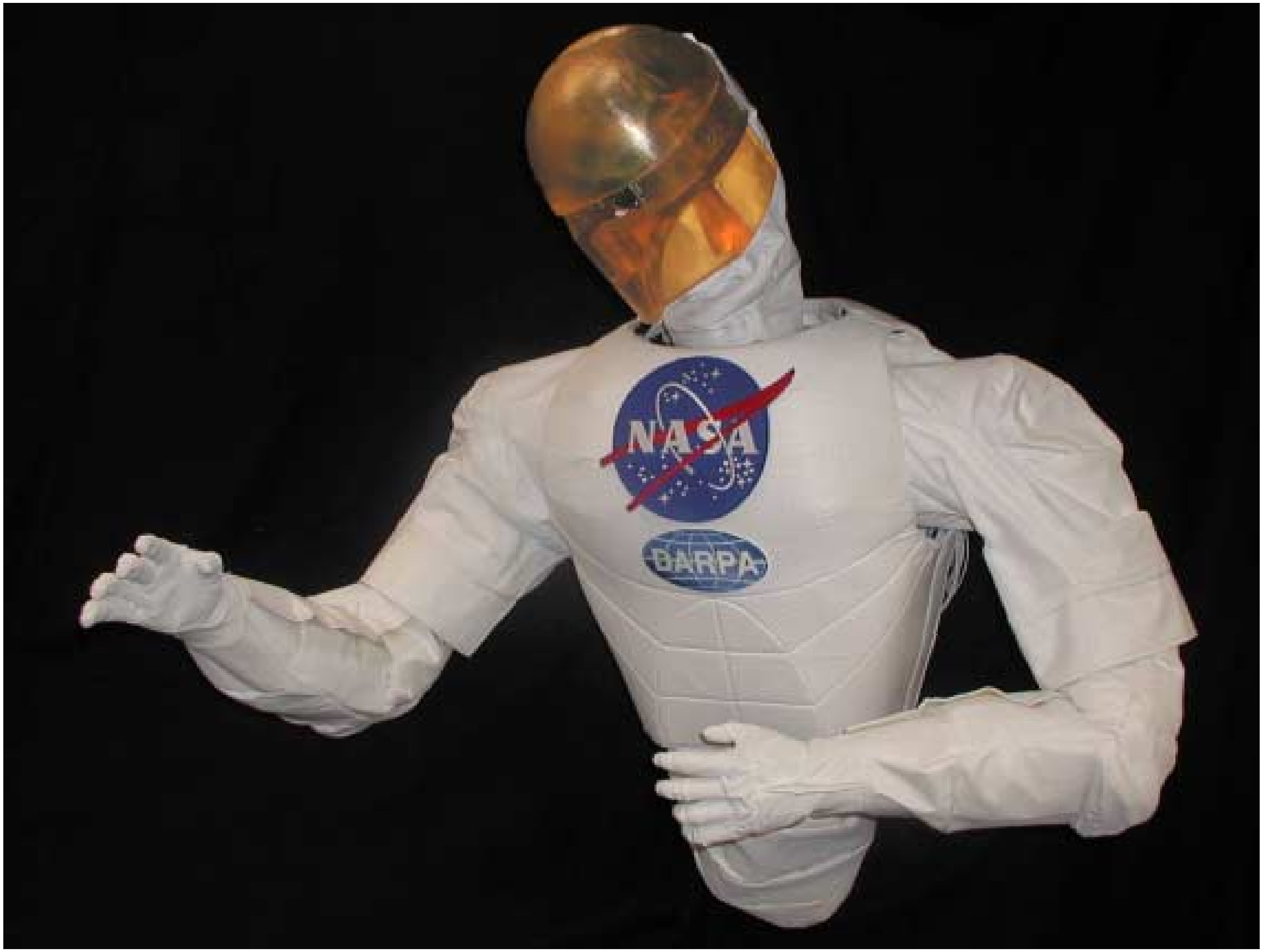
NASA's Reliance on EVA

- **Long Term Investment in EVA capabilities**
  - **Shuttle and Station**
  - **Hundreds of Satellites**
- **EVA roles**
  - **Contingency**
  - **High Dexterity**
- **Future Missions**
  - **Telescopes \ Platforms**
  - **Interplanetary Vehicles**
  - **Surface Operations**



STS-103 Astronaut Claude Nicollier works at a storage enclosure, using one of the Hubble power tools

Robonaut (JSC Anthropomorphic EVA Robot)



Robonaut Technology Demonstration

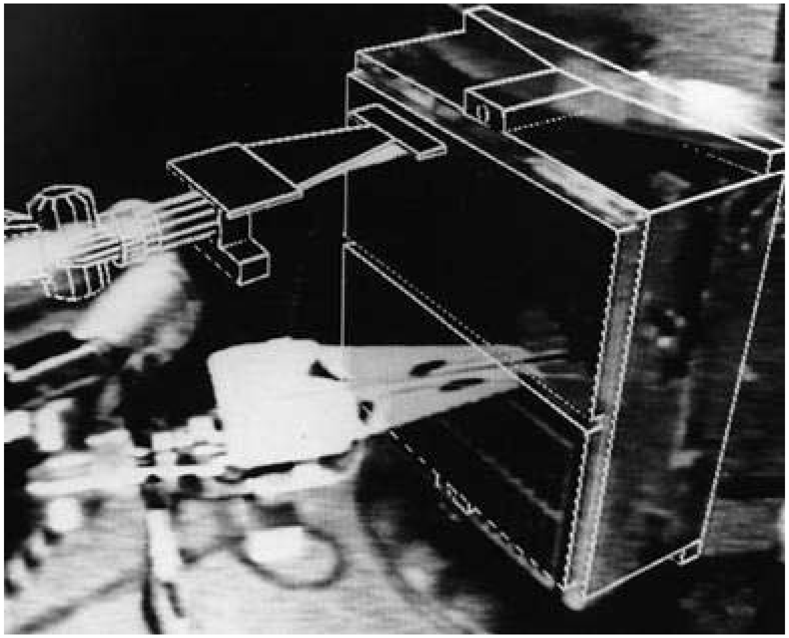
Multi-Agent Truss Assembly (JSC, N. Currie)

Time Delay Teleoperation Task

JPL-GSFC Satellite Servicing under Variable Communications Latency

ORU Change-Out Task using Predictive Graphics and Compliance Control

JPL Operations Site



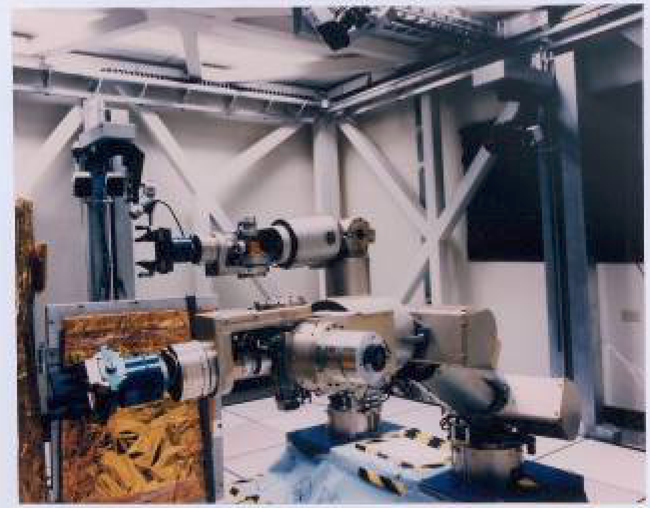
GSFC Servicing Site

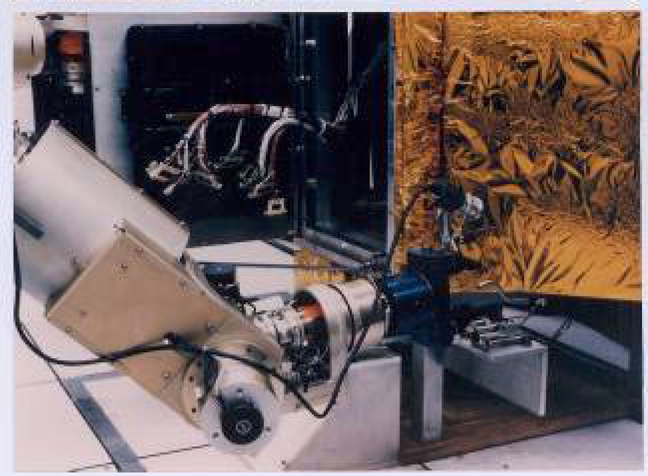
6-to-15 seconds asynchronous communications delay

High Dexterity Teleoperation (JPL TROPICS Lab)

ADVANCED TELEOPERATION WORKSTATION
Dual-Arm Control with Graphics Displays
for Task Preview and Time-Delayed Operations

ADVANCED TELEOPERATION WORKCELL
Technology Validation for a Simulated
Solar Max Satellite Repair Task





Assistive Task Viewing & Visualization

Intelligent Viewing Control

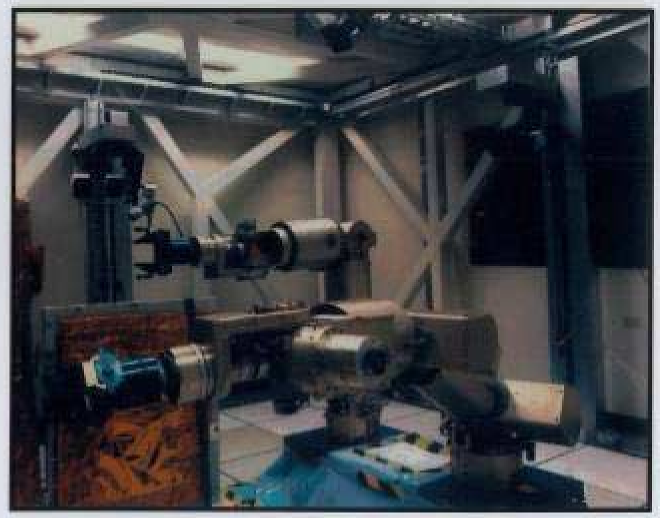
MACHINE INTELLIGENCE ASSISTS THE OPERATOR

<> Operator actions simultaneously control cameras, graphics, and manipulation
<> Machine intelligence plans and selects feasible camera views
<> Synthesized views are available when real camera views are obstructed

ENABLING CONCEPTS:

<> Manipulation and viewing are semantically linked and time-synchronized
<> Viewing actions are matched to granularity of control actions
<> Virtual Reality Calibration is fundamental to operator confidence in graphics-based viewing

Operator's Console



TROPICS Remote Site

Behavioral Control Compensation

Intelligent Motion Control

<> Satellite thermal foil removal task involves puncture and slicing of Kapton tape along 2mm x 400mm groove, while complying with top and bottom edges.

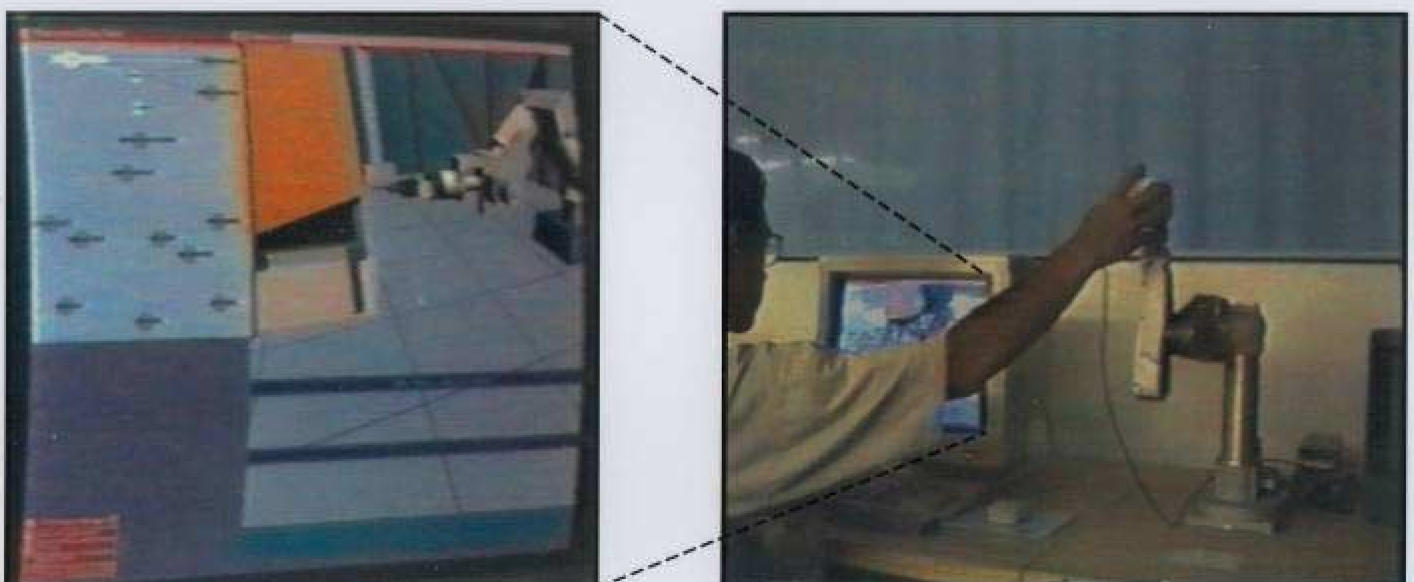
<> Behavior controller implemented at the JPL TROPICS Lab remote site (VME/VxWorks computers and the dual 8 DOF AAI arms) -- cooperative with UPenn.

H/R Cooperative Task Execution

Remote Operations with IMC

<> Cross-country operation of JPL's IMC from the Teleprogramming System of the University of Pennsylvania (Stein, Sayers, & Paul) in August, 1994

<> UPenn operator's screen displays graphic model of remote site of JPL TROPICS Lab and the behavior controller state diagram.

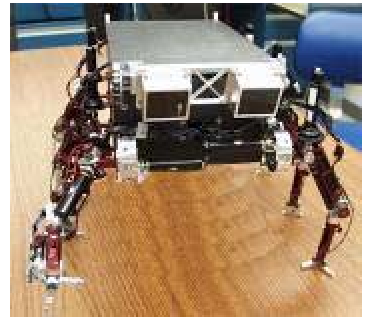


Surface Mobility Examples

Examples: Surface Mobility R&D

FIDO

Sample Return Rover (SRR)



LEMUR

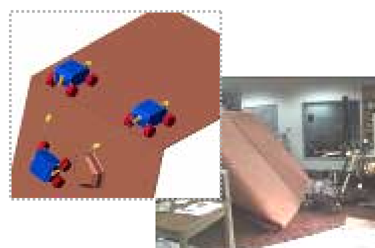
Inflatable Rover

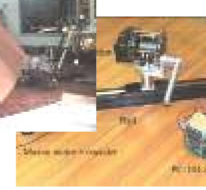
MER Egress Rover

MER Soil Interaction

Robot Work Crew

All Terrain Rover

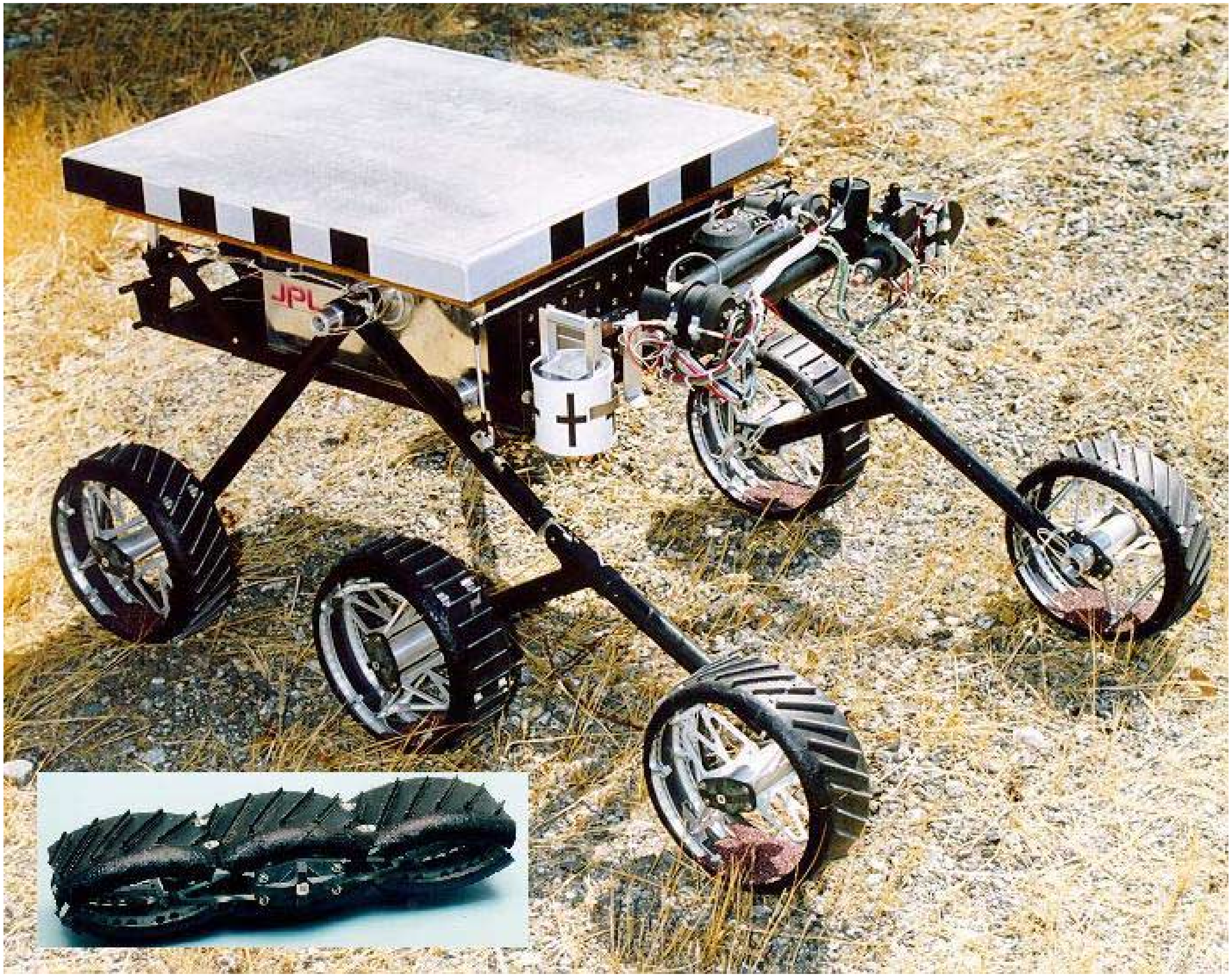




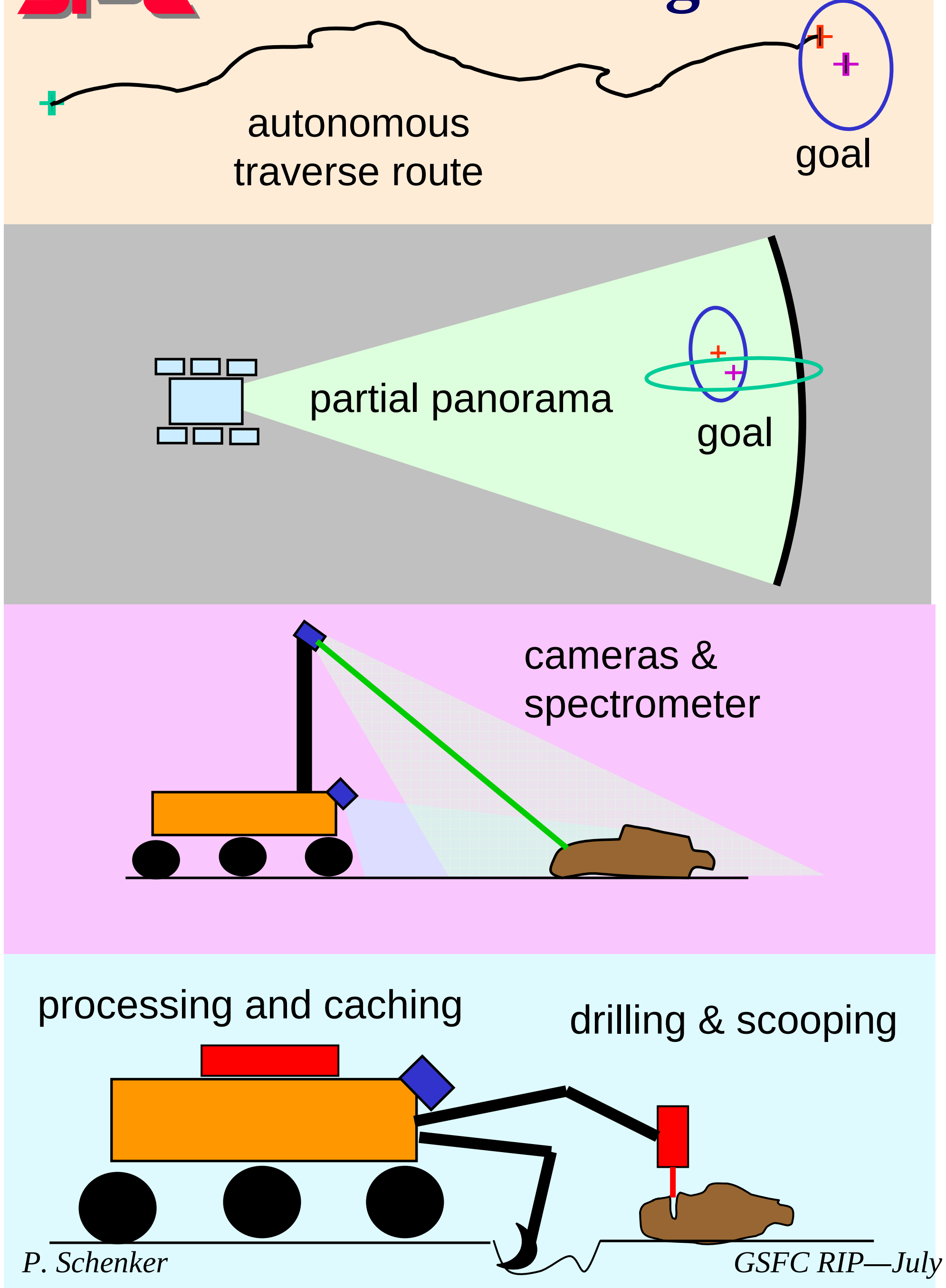
Cliff-bot

*** Planetary Robotics Laboratory**
http://prl.jpl.nasa.gov

Surface Mobility (Mechanization Advances)



Challenges to Mobile Autonomy



AUTONOMOUS TRAVERSE:
Autonomous traverse, obstacle avoidance, and position estimation relative to the starting position.

APPROACH & INSTRUMENT PLACEMENT:
Autonomous placement of a science instrument on a designated target, specified in imagery taken from a stand-off distance.

ONBOARD SCIENCE:
Autonomous processing of science data onboard the rover system, for intelligent data compression, prioritization, anomaly recognition.

SAMPLING:
Sampling, sample processing, and sample caching through development of controls for new system components.

Making Robots Smarter

"On-board Intelligence", and layered architectures

Servo-level

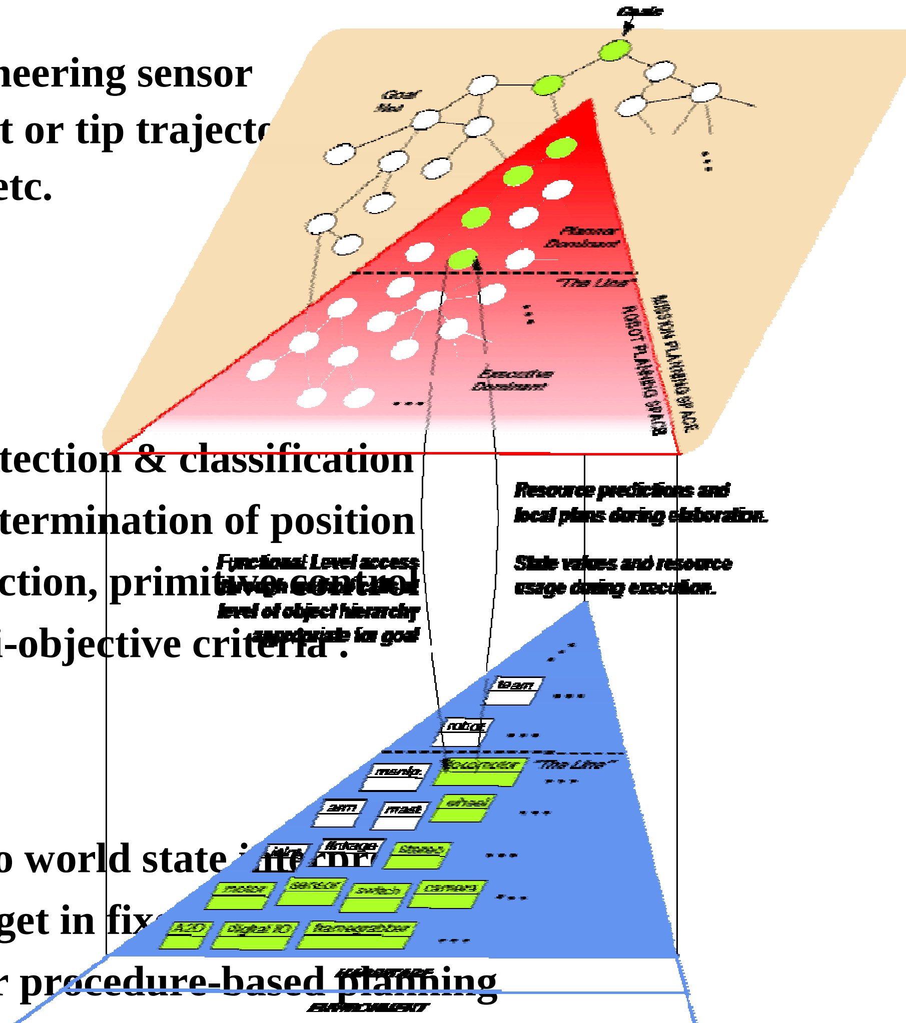
- **Continuous control loop wrapped around engineering sensor**
- **Example: move robot arm along specified joint or tip traject**
- **Aka. sensory-motor, Cartesian motor control, etc.**
- **May be fixed point control or adaptive**

Behavior-level

- **Task primitive executed in response to state detection & classification**
- **Example: close robot end effector on visual determination of position**
- **Aka. reflexive, reactive, skill-based, action-selection, primitive control**
- **May be parameterized and/or respond to multi-objective criteria".**

Cognitive-level

- **Planning, scheduling, monitoring in response to world state interpr**
- **Example: rover commanded to traverse to target in fix**
- **Aka. artificial intelligence, deliberative and /or procedure-based planning**
- **Based on a combination of prior world knowledge and environmental perception**



Space Robotics Technologies & Operational Metrics

MANIPULATION
- EOA speed
- Accuracy
- Precision
- Dexterity
- Power efficiency
- Backdrive-ability
- Thermal stability
- Calibration

MOBILITY
- Ground speed
- Ground pressure
- Traversability
- Localization
- Cone of stability
- Climb rate
- Holonomicity
- Self-rightability

ON-BOARD INTELLIGENCE
- Resolution (multi-scale representation)
- Scalability (computational complexity)
- Completeness (search depth, breadth)
- Generalization (of classes, objects)
- Learning (from instances, training, etc.)
- Contingency (recursion, nonlinearity)
- Fidelity (binarization of analog models)
- Robustness (to partial, priced, and contaminated information …)

PERCEPTION
- Accuracy
- ROC (false positives)
- Calibration
- Weather and dust degradation
- Robustness (wrt. albedo, texture, etc.)
- Fidelity (of featural representation/recovery)
- Color and textural feature discrimination
- Generality (extrapolation, training, learning)
- Computation (Bits/Cycles for given function)

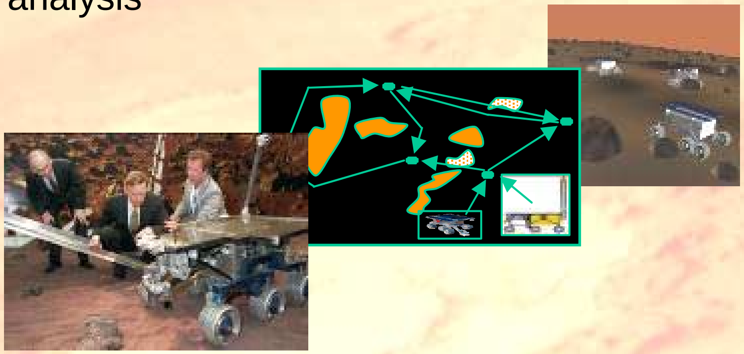
Example (System Operational Metrics)

Background image: MER 2 with Sojourner model

Rover Testbeds & Field Trials

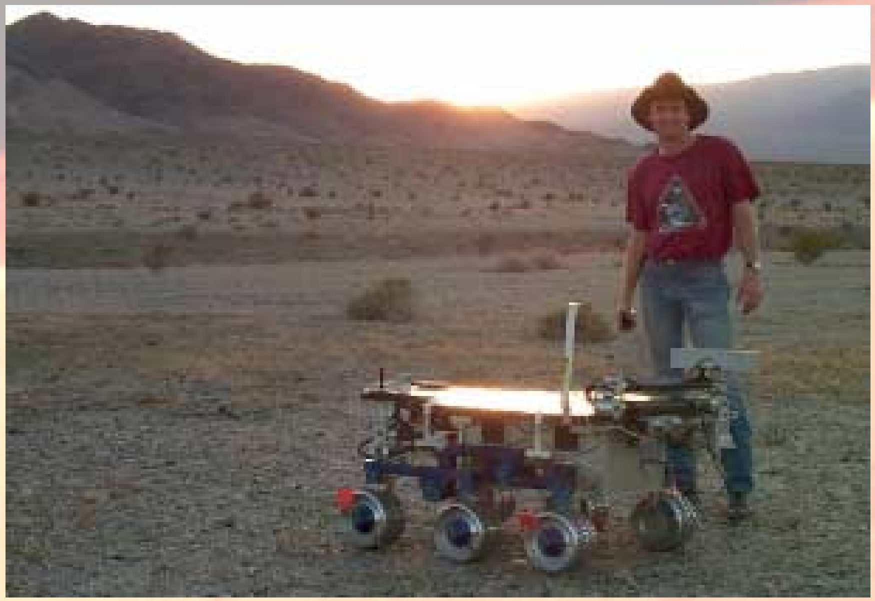
Testbed Use

- Component technology integration and test
- Intelligent Systems (IS) and other initiatives technology product infusion/leverage
- Development and verification of human/robot operation interfaces, planning/visualization
- Quantitative system-level performance evaluation & characterization
- Ground truth, field validation, and science community tie-ins for relevant experiments
- Opportunity for advances in synergistic science operations and on-board science analysis



P. S. Schenker, et al., "Planetary Rover Developments Supporting Mars Exploration, Sample Return and Future Human-Robotic Colonization," *Autonomous Robots*, No. 2/3, March/May, Vol. 14, pp. 103-126, 2003 (Special Issue on Robots in Space)

"FIDO (Field Integrated Design & Operations) Rover"

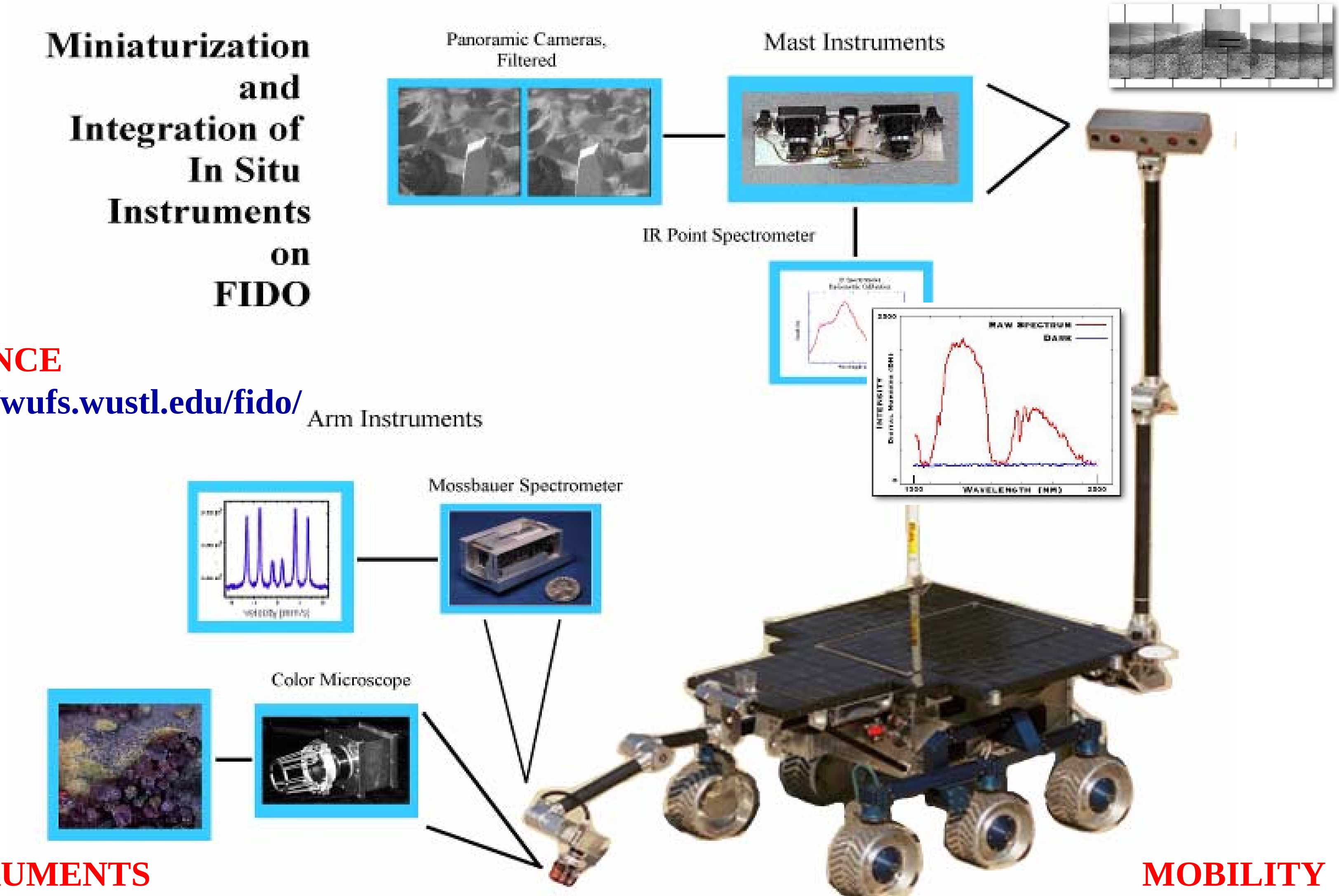


Supporting Technology Development

- Comprehensive control architectures for multiple, interacting, instrumented planetary and on-orbit robotic systems
- On-board intelligence for automated science sequence planning, error handling and recovery; visually referenced mobility and manipulation
- High-fidelity simulations for concept development
- End-to-end capability to emulate science-relevant remote operations, including critical program elements of human/robot interaction & cooperation

Field Experiments & Technology Validation

Integrating Science Operations, Instruments and Mobility

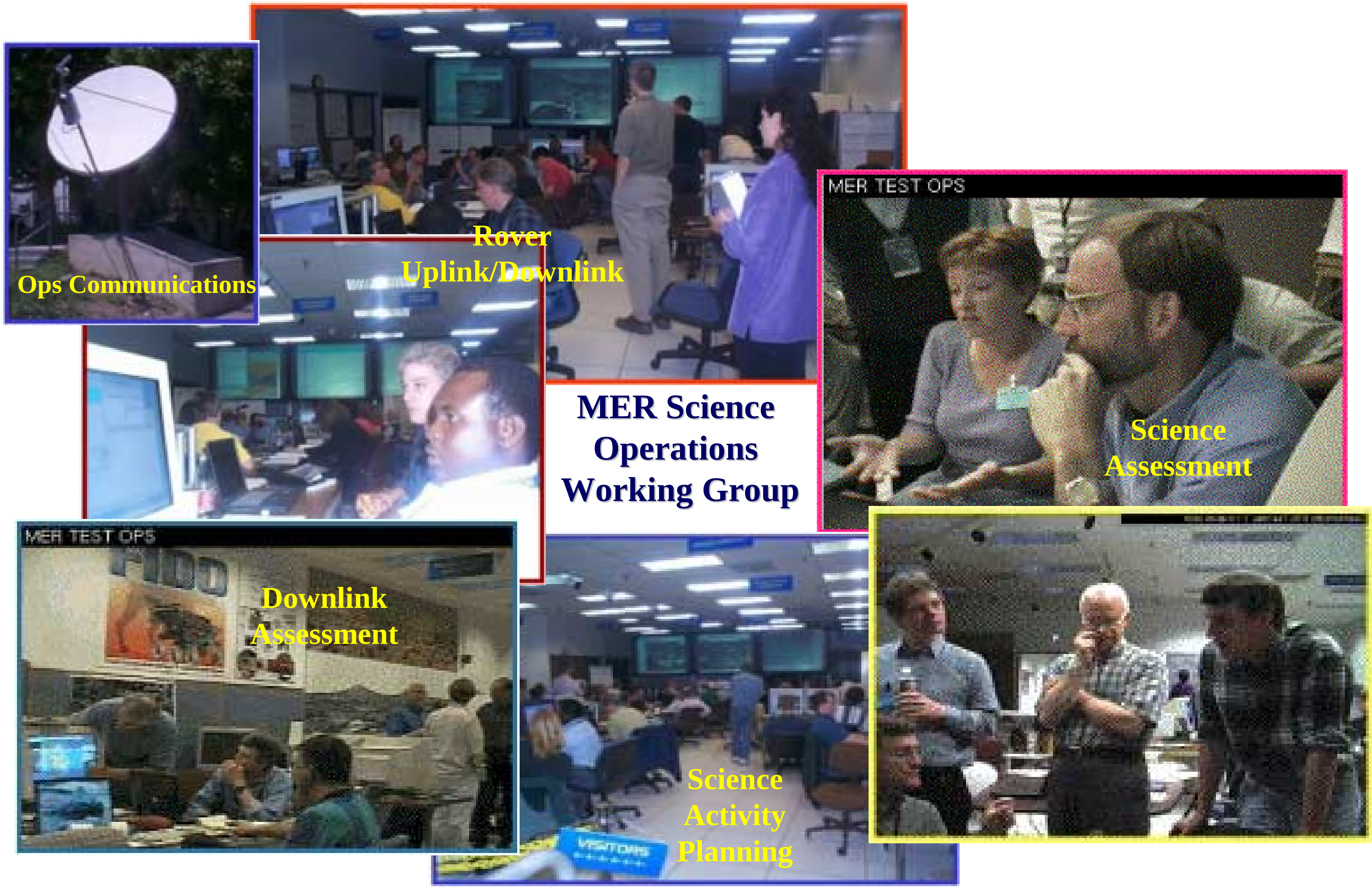


SCIENCE
http://wufs.wustl.edu/fido/

INSTRUMENTS
http://fidoinstruments.jpl.nasa.gov/

MOBILITY
http://fido.jpl.nasa.gov/

Field Test Mission Operations from JPL-PRL



R&D Payoff: Technology Infusion to MER

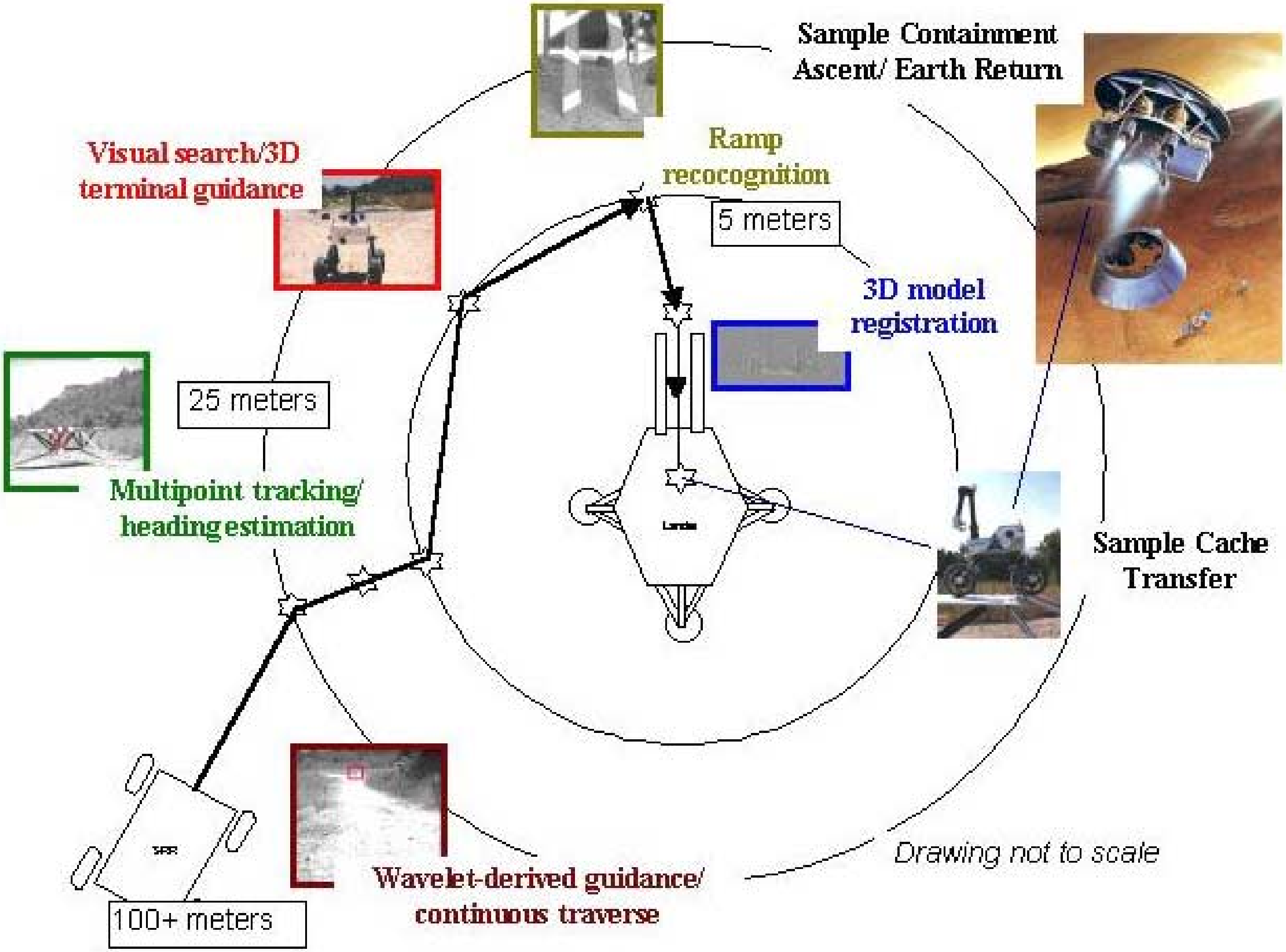
(from the Mars Technology Program and Predecessors)

	Technology	Funding Source	Description	PI/Technologist
1	Long Range Science Rover	NASA (Code R and MTP)	Provides increased traverse range of rover operations, improved traverse acuracy, landerless and distributed ground operations with a large reduction in mass	Samad Hayati Richard Volpe
2	Science Activity Planner	NASA (Code R and MTP)	Provides downlink data visualization, science activity planning, merging of science plans from multiple scientists	Paul Backes Jeff Norris
3	FIDO: Field Integrated Design and Operations Rover	NASA (MTP)	Developed TRL 4-6 rover system designs, advancing NASA capabilities for Mars exploration; demonstrated this in full-scale terrestrial field trials, Integrated/operated miniaturized science payloads of mission interest, coupling terrestrial field trials to	Paul Schenker Eric Baumgartner
4	Manipulator Collision Prevention Software	NASA (MTP)	Computationally efficient algorithm for predicting and preventing collisions between manipulator and rover/terrain.	Eric Baumgartner Chris Leger
5	Descent Image Motion Estimation System (DIMES)	NASA (Code R and MTP)	Software and hardware system for measuring horizontal velocity during descent, Algorithm combines image feature correlation with gyroscope attitude and radar altitude measurements.	Andrew Johnson Yang Cheng
6	Parallel Telemetry Processor (PTeP)	NASA (Code R and MTP)	Data cataloging system from PTeP is used in the MER mission to catalog database files for the Science Activity Planner science operations tool	Mark Powell Paul Backes
7	Visual Odometry	NASA (MTP)	Onboard rover motion estimation by feature tracking with stereo imagery, enables rover motion estimation with error < 2% of distance traveled	Larry Matthies Yang Cheng
8	Rover Localization and Mapping	NASA (MTP)	An image network is formed by finding correspondences within and between stereo image pairs, then bundle adjustment (a geometrical optimization technique) is used to determine camera and landmark positions, resulting in localization accuracy good for trav	Ron Li Clark Olson et. al.
9	Grid-based Estimation of Surface Traversability Applied to Local Terrain	NASA (Code R and MTP)	Performs traversability analysis on 3-D range data to predict vehicle safety at all nearby locations; robust to partial sensor data and imprecise position estimation. Configurable for avoiding obstacle during long traverse or for driving toward rocks for	Mark Maimone
10	Lithium-Ion Batteries	NASA (Code R and MTP), Air Force (AFRL)	Significant mass and volume savings (3-4 X) compared to the SOA Ni-Cd and Ni-H2 batteries.	Richard Ewell Rao Surampudi

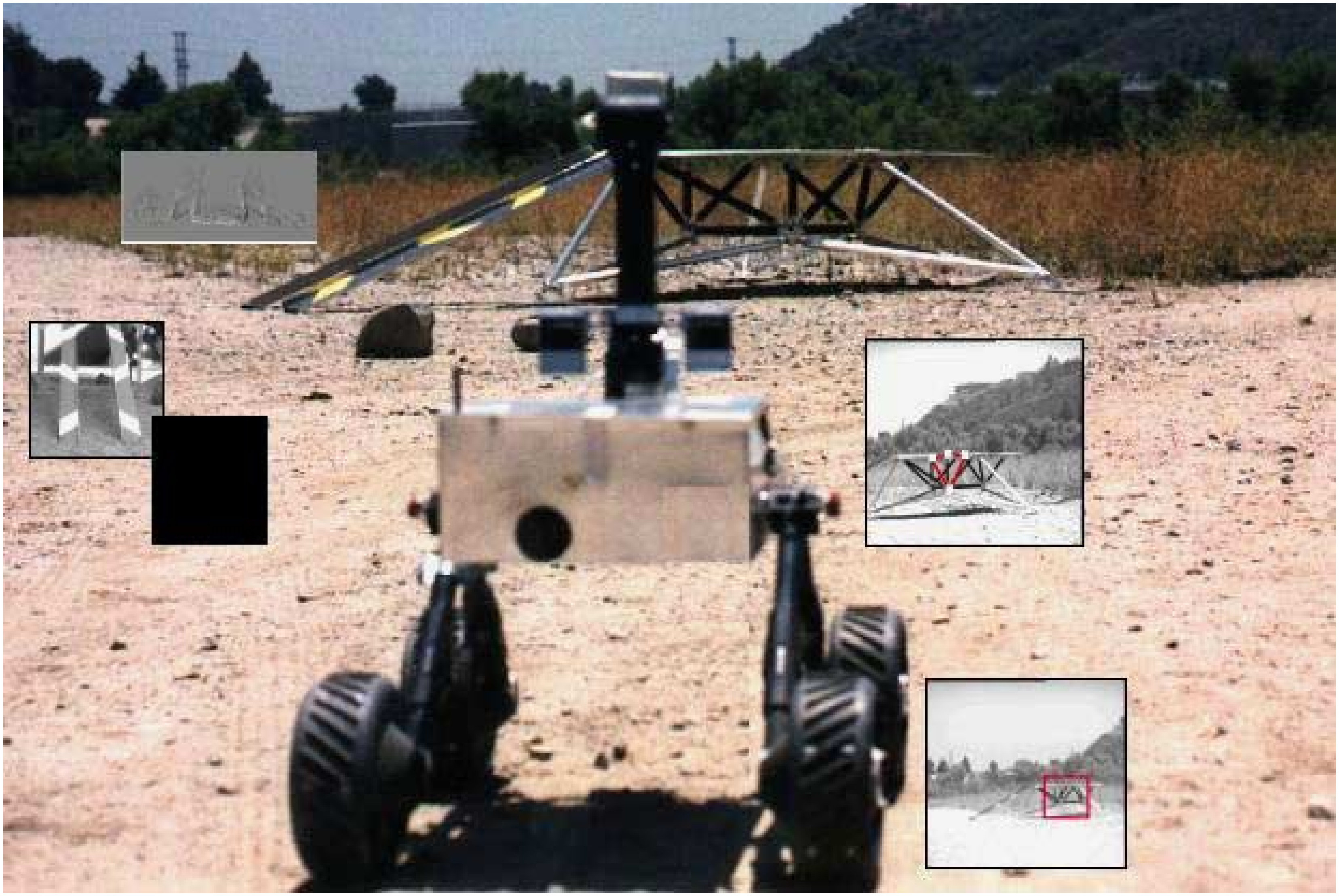
Lander Detection and Rendezvous for MSR

- Long range lander tracking/navigation (Fused line and wavelet-derived texture features for target detection, tracking and long-range approach from >100 meters)
- Mid range lander tracking/navigation (Multi-line feature extraction and rover-to-lander pose estimation using known lander geometry for mid-range approach at 5 – 25 meters)
- Lander ramp rendezvous (Pattern extraction, recognition, and precision registered guidance into lander via rover-to-ramp pose estimation on final approach at 0.2 – 5 meters)
- Continuous-motion mobility: high speed hazard detection and avoidance for in-route approaches in non-benign terrain
- Performance: Average long range heading error was <0.5°, average mid-range distance error <6.5%, average close range ramp alignment error < 2cm.

Automated Lander Rendezvous - MSR Scenario



Automated Lander Rendezvous - Field Experiments

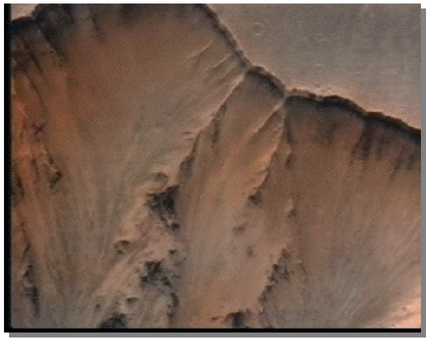


High Risk Access Surface Mobility

- *High risk, hard to access* **planetary/lunar locations and exciting science are linked.**
- *Current surface mobility mechanisms* **and control paradigms are not well suited.**
- *Alternative mobility solutions* **include aerial access, but the danger of surface collision is high, and the precise, repeatable engagement of multiple targets with controlled application of science instruments is unlikely.**
- *New mobility architectures are needed* **that make intelligent use of their underlying sensing, control, & mechanization to respond reflexively and reconfigurably for improved terrainability and stability.**
- *Multi-agent systems* **can mitigate risk through cooperative problem solving strategies.**

Lunar Aristarchus Plateau

Aitken Impact Basin, South Lunar Pole



Potential water outflows, Mars cliff face

Single Rover Steep Terrain Mobility

Rover State Estimation and Predictive Control (JPL)

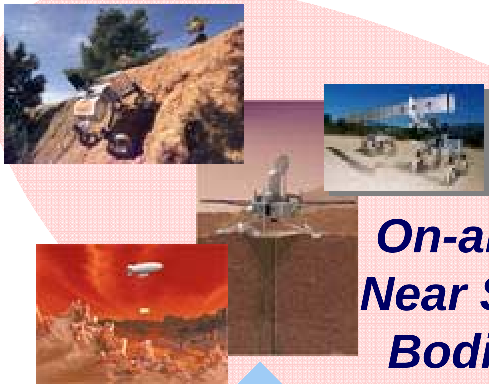
- Successfully demonstrated on SRR in Arroyo Seco at slopes of up to 50^o, wherein fixed-geometry control was shown to fail
- Provides stability with respect to *slip and tip-over*
- Uses visually sensed range map, spline parameterization, and INS for model-based predictive state estimation
- Predictive reconfiguration encoded in a Look-Up-Table: developed via off-line simulation and used online for control of rover

Physics Based Planning & Reconfiguration (MIT/JPL)

- Successfully tested in Arroyo: trades off two objective functions for *tip-over* (high priority) and ground clearance (lower priority)
- Uses INS, kinematics, and quasi-static model to stabilize rover in "bounding c.g." volume; reconfigures 2 DOF arm and 2 x 1 DOF shoulders (4 DOFs total)
- Work conducted in residence at JPL by Professor Steven Dubowksy and MIT Ph. D. students (Mech. Engrg.)

Multi-Robot and Human-Robot Systems

Commonality of Architectures and Component Technologies



On-and-Near SSE Bodies

Enabling Technologies

On-Board Intelligence

Manipulation

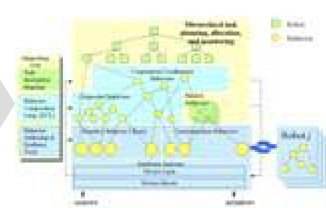
Mobility

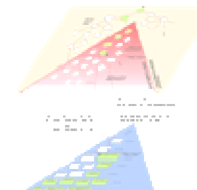
Human/Robot System Architectures

- Distributed & cooperative agents
- Reconfigurable, redeployable robots
- Telerobotic & teleprogrammed control
- Visualization & designation interfaces
- Sequencing & contingent planning
- Reactive, reflexive system GN&C
- Sensory fused global perception
- Multi-modal operations interfaces
- Teleoperation with latency

Unified Human/Robot Operations

- Cooperative H/R work on orbit and surfaces
- Surface preparations for human explorers
- Instrument deployments for mission crew
- Robot assistance to EVA exploration
- Robotic risk mitigation to spacecraft and crew safety (inspection & intervention)





Needed Capabilities

Manipulative instrument placement

Sample processing and handling

Navigational long range traverse

Rough terrain mobility & safety

Multi-sensory state estimation

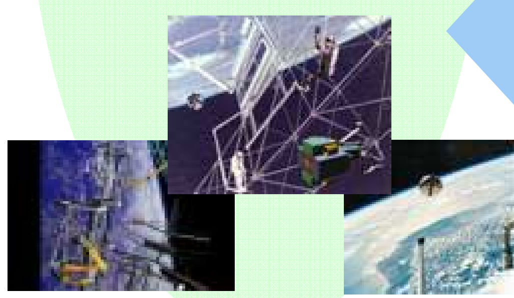
Visual tracking, localization

Local area mobility planning

Cooperation of multiple robots

Activity sequencing / visualization

In-Space



Needed Capabilities

Manipulation of parts / assemblies

Traverse of large space structures

Grapple dexterity on trusses, etc.

Transport, docking, and deployment

Multi-sensor modeling / recognition

Visual tracking, localization

Local structure mobility planning

Cooperation of multiple robots

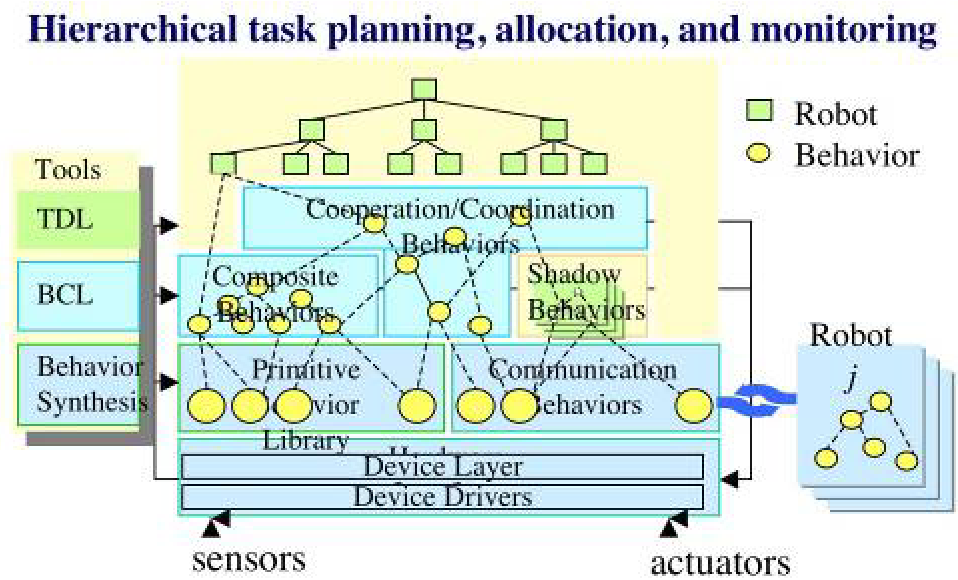
Activity sequencing / visualization

Networked Robotics as a Research Paradigm

- Fundamental view of system elements as resources to be mapped
- As part of modular, hierarchical, extensible system architectures
- No underlying assumptions of homogeneity across system elements
- Distribution and decentralization of system functions are givens
- Spatial non-locality and temporal non-synchronicity are constraints
- Environmental information is “partial, priced and contaminated”
- Time-sequenced execution strategies to bound error propagation
- Various supervisory control strategies re. “perceptual chunking”
- Human resources as agents “on” or situated “in” system-of-systems
- Open, adaptive models for arbitration of control and sensory fusion
- Related perception-action primitives, flexible hierarchical linkages
- With a view to system reconfigurability re. evolving task structure
- Interaction of system agents is often bi-lateral, potentially adaptive
- IROS 2004 Workshop, *NR: Issues, Architectures & Applications*

Toward Networked Robotic Systems

Robotic Work Crew Demonstration

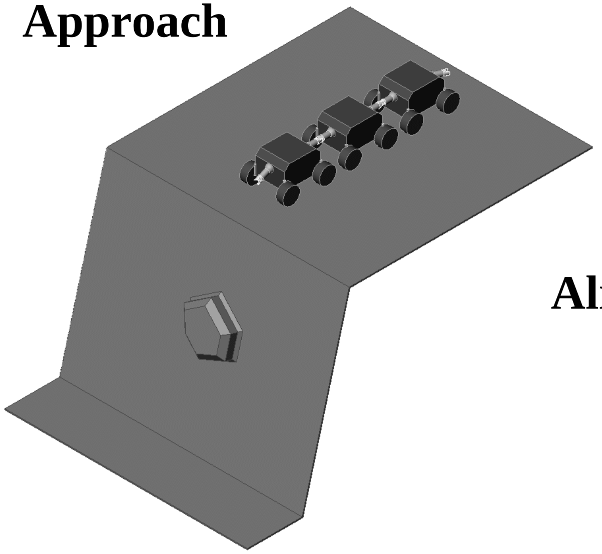


- **<u>M</u>ixed <u>I</u>nitiative <u>C</u>ontrol <u>A</u>rchitectures support human and robot multi-agent cooperation**
- **Robots tightly, autonomously coordinate interactions to perform complex physical tasks**
- **Layered autonomy coordinates fast, reactive behaviors and higher level decisions/planning**
- **The human agent/s can be both supervisor and work team participant/s as appropriate**
- **Networked Robotics enables flexible extension, decomposition, & remapping of resources**
- **This provides capability for scaled operations over large areas and multi-task objectives**

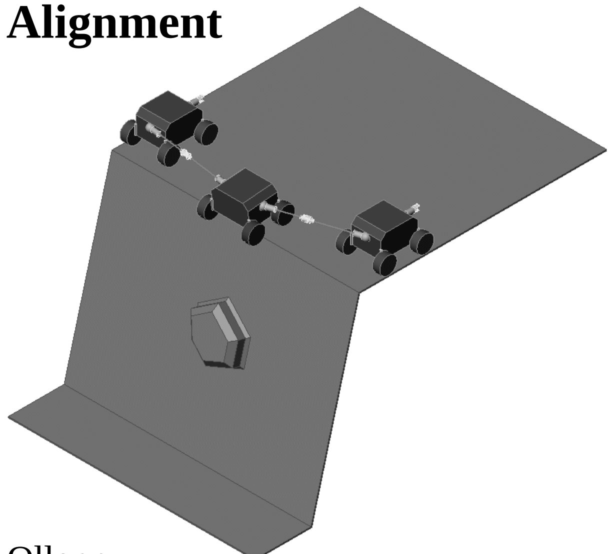
Cliff Descent by Cooperative Robots

Robots are a "coarse-grained" modular reconfigurable system operating under a hierarchical control architecture ("CAMPOUT"*, JPL 1999)

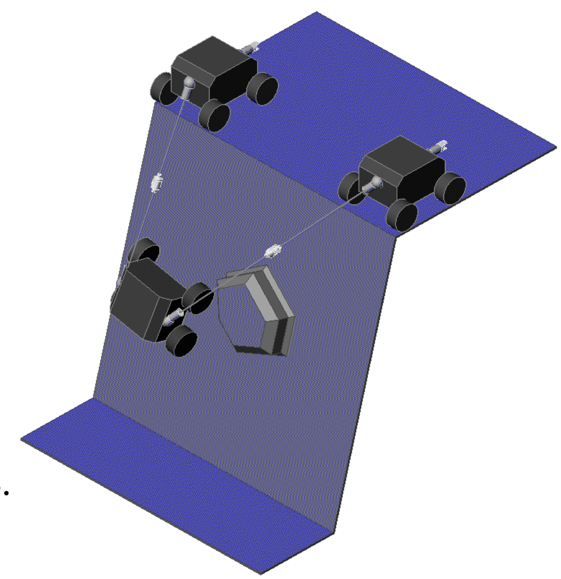
Approach



Alignment

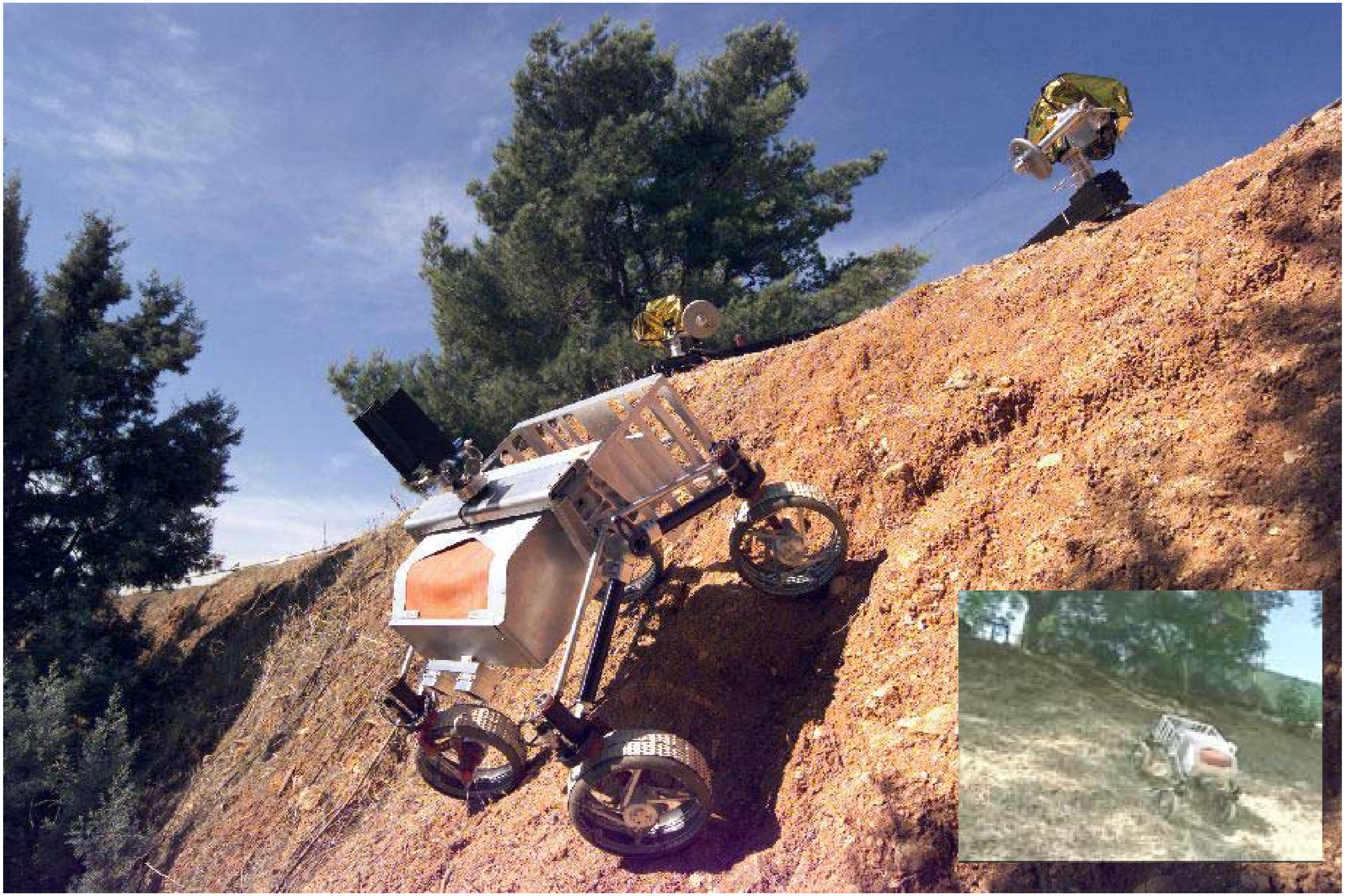


Descent

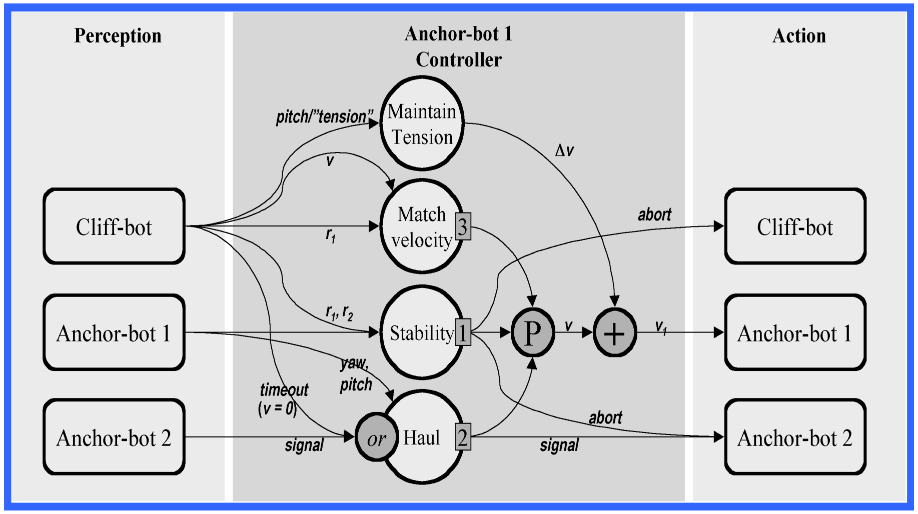


* T. Huntsberger, P. Pirjanian, A. Trebi-Ollennu, H. Das, H. Aghazarian, A. Ganino, M. Garrett, S. S. Joshi, P. S. Schenker, "CAMPOUT: A Control Architecture for Tightly Coupled Coordination of Multi-Robot Systems for Planetary Surface Exploration," *IEEE Transactions on Systems, Man, and Cybernetics* (Special Issue on Collective Intelligence), accepted for publication, to appear fall, 2003.

Multirobot Cooperation for Steeper Terrain Mobility



Distributed Mobility Control



"Cliff-bot"

- A behavior network is used to control group of 3 rovers—two anchored at top and third navigating on cliff face
- Behavior coordination is for *Maintain Tension*, *Match Velocity*, *Stability*, and *Haul* behaviors; with Stability given top priority
- Includes way-point based navigation and stability diagnosis & recovery on slopes > 60° over distances of 10-to-15 meters (as determined by physical site access restrictions). Two "anchor-bots" work under collective estimation and distributed control (CAMPOUT) with the descending "cliff-bot" to enable a robust, fault-free traverse in arbitrary directions.

Multi-Agent Robotic Cliff Access

Overview of Problem

T. Huntsberger, V. A. Sujan, S. Dubowsky, and P. S. Schenker, **"Integrated System for Sensing and Traverse of Cliff Faces,"** in Proc. SPIE Aerosense, Vol. 5083, April 22-24, 2003

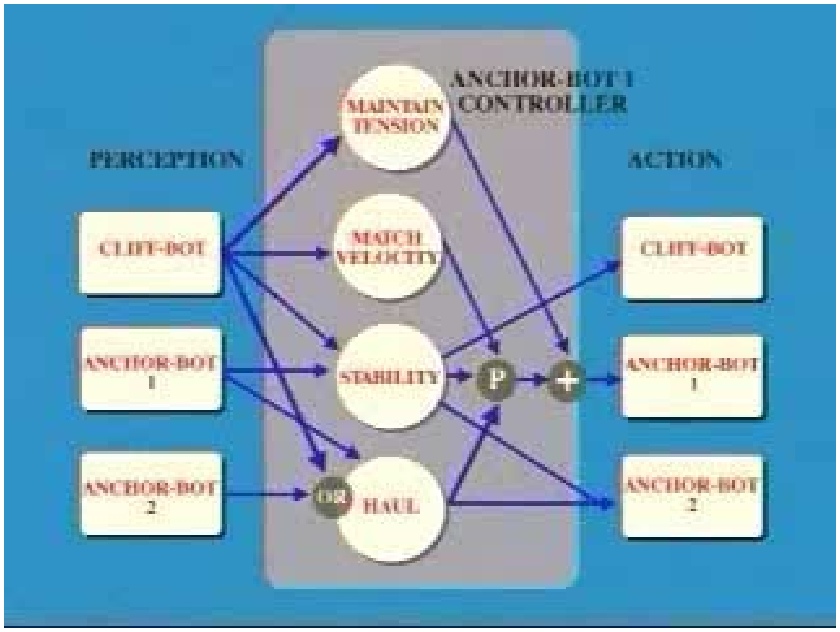
Unstructured, unknown cliff surface

Four interacting cooperative robots

- Two "Anchor" rovers (Anchorbot)
- One cliff descent rover (Cliff-bot)
- One cliff surveyor rover (RECON-bot)
- Limited sensor suite
- Limited mobility

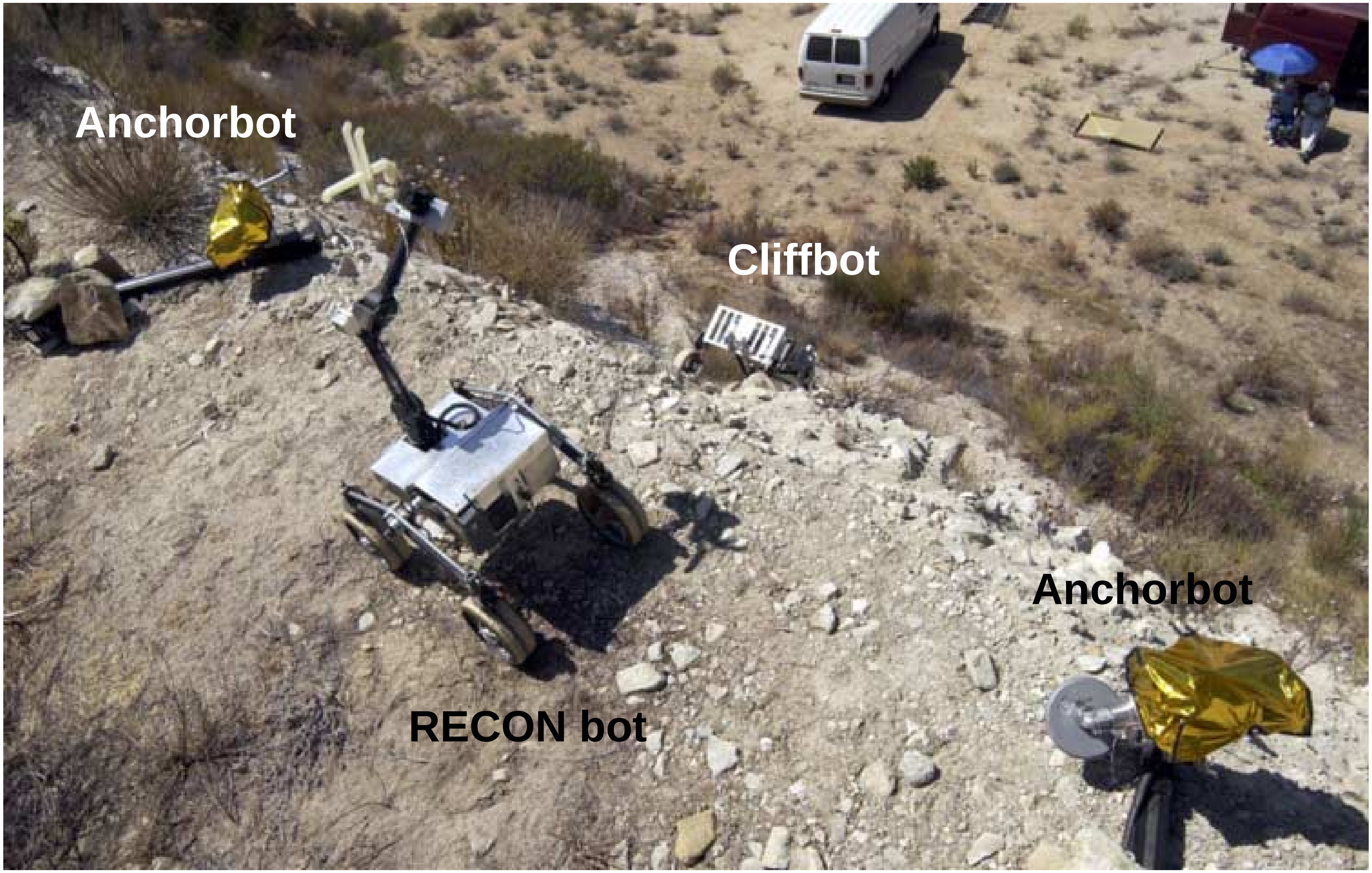
Coordinated robot control

- Explore environment
- Maintain Cliff-bot stability
- Waypoint navigation



Behavior coordination: *Maintain Tension*, *Match Velocity*, *Stability*, and *Haul*

Distributed Sensing - Field Experiments



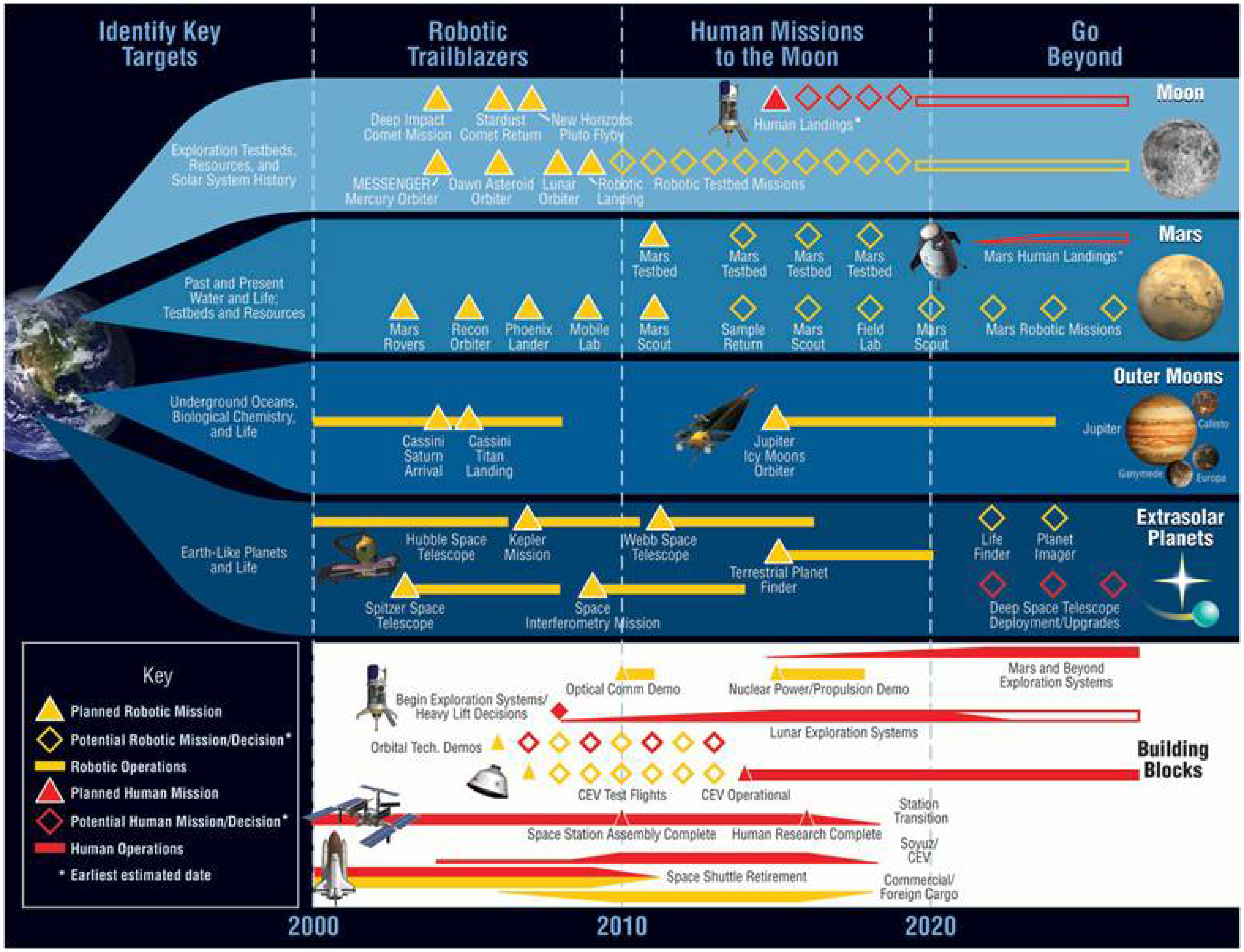
Vision for Space Exploration

The Vision for Future NASA Space Exploration *

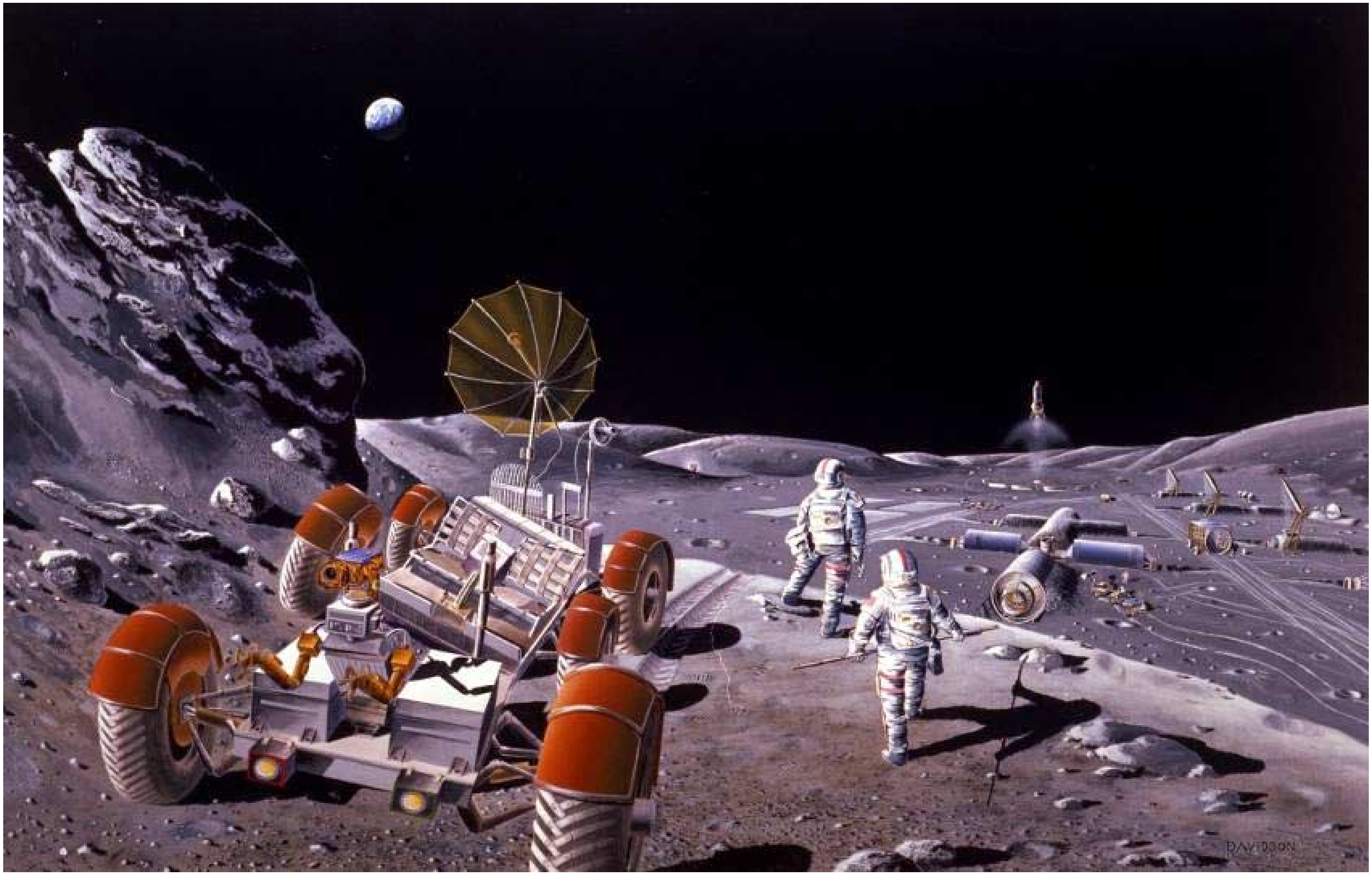
- **Moon, Mars and Beyond**
- **Human and Robotic exploration as complements, ultimately H-R**
- **Robotic trailblazers that buy down risk (human and resources)**
- **Science still a focus, but of lesser priority the closer you get to earth**
- **Secondary at the moon, with *in situ* resources, mission design V&V, and infrastructure pre-eminent**
- **Primary in the earlier Mars mission sequences/pathway, but still focused to sustainable human habitation and safety**
- **Primary and fundamental to early exploration in deep space, both past Mars, and observation platforms for outside the solar system**

* ***The Vision for Space Exploration***, February 2004, National Aeronautics and Space Administration, NP-2004-01-334-HQ, Washington, DC 20546.

Exploration Roadmap



Lunar Base



Developmental Strategy

- Go to moon, do relevant science/resource assessment for longer term habitation and Mars/deep space mission staging, prototype-validate H/R mission design & operations for possible Mars application
- Continue a strong program of robotic Mars science, evolving from more fundamental geochemistry and astrobiology to future resource utilization and human habitat precursor deployment-operations
- Construct and deploy, by necessary means and orbits, telescopes and support systems enabling long duration astro-chemical assessments of other non-SS planetary bodies
- Pursuant to the previous, build an in-space infrastructure to bring operational risk, launch/transport staging and system risks (human safety and robotic cost impacts) within as yet unspecified limits
- Develop related reusable modular architectures (re. mission resources and logistics) that provides a time-integrated, major reduction of costs?

Mars H/R Science

Mission Systems Engineering Perspective

- **All space systems are human-robotic by their definition**
- **Distinguished only by distance of the human from robot**
- **Human "in, on, near, and far" regarding task activity**
- **STS crew, lunar rover driver, STS/ISS teleoperation, and MER ground sequencing experience base, etc.**
- **As human and robotic system elements move apart, there are logical transitions in system design**
- **While only an approximation of all possible human-robotic interactions, the above system factors have major operational impacts**

System Scaling Effects

- From proximal human actions to distal supervised automation
- From continuous interaction to time-delayed task sequencing
- From high fidelity sensory perception to low fidelity task representation (in part due to communications limitations)
- From relatively agile mobility and dexterous manipulation to highly structured, somewhat inflexible tele-robotic motions
- From in-the-loop reactive and cognitive human interaction, to programmed safe robotic modes of operation, and off-line anomaly assessment

Three Operational Regimes

Human-Present

- **Humans working directly with robots on-site (teams)**

Teleoperative-Telepresent

- **Humans close enough to robots to use them as high fidelity extension (viewing, manipulation, driving)**

Supervised Autonomy

- **Humans far away, using their cognitive skills to analyze, plan, diagnose and program robot action, with remote command and data handling being geographically distributed & decentralized**

Mission Logistics and Limitations

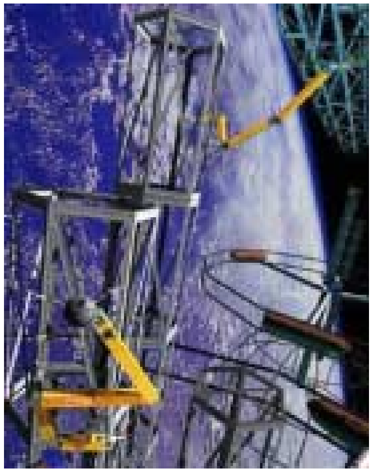
- **Work by humans *in situ* (even with current EVA suit limitations) will progress at 10-to-100x robotic capability for the foreseeable future, but lags terrestrial shirt-sleeve performance by a comparable factor**
- **Major anomalies encountered in teleoperative systems may require direct human EVA (if feasible)**
- **Minor anomalies encountered by telerobotic systems (those with elements of automation that are shared by, or assist human manual control) might be resolved by robotic action**
- **Major anomalies in telerobotic operations, including fully supervised automation of deep space activity by ground controllers will likely lead to mission failure**

Comments, Summary, and Conclusions

Summary - Future Goals

Exploration Systems:

- **Expeditions on-or-near solar system bodies, including sustained robotic access to very rugged and adverse environments (lunar, planetary, and related small bodies). Robotic capabilities will evolve to human / robotic (H/R)**
- **In-space assembly, inspection, and maintenance of instruments or facilities, with extension to surface habitat development and servicing**



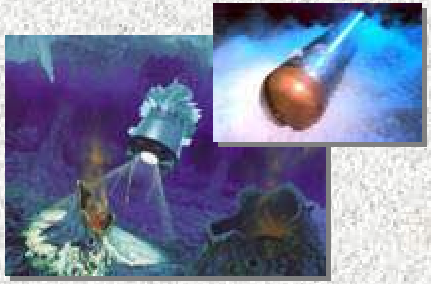
Required Capabilities Include:

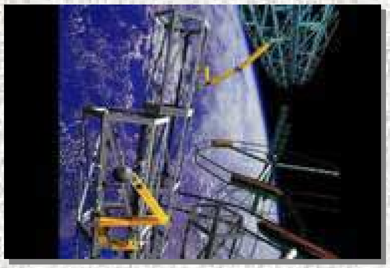
- **Dexterous human/robotic (H/R) work systems; agile aerial, surface, and sub-surface autonomous explorers**

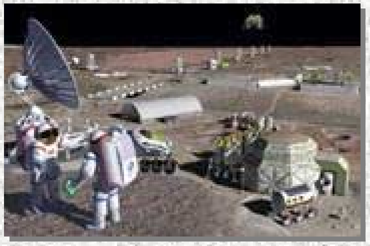
  … "go where we can't—survive—do breakthrough science"
- **Advanced mobility, manipulation, and on-board intelligence technologies, enabling human/robotic task interactions and multi-robot cooperation.**

  … "autonomy as integrating bridge for large scale systems"

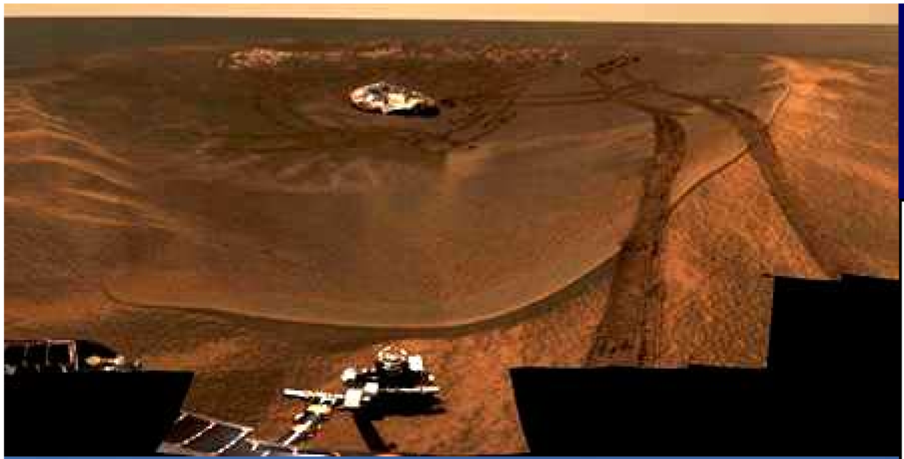
Diverse Mission Applications







Planetary Mobility: Today



Mars

– Ability to traverse moderately rocky surfaces at <500m/sol
– Vulnerable to low bearing strength deposits (sand and dust, particularly on slopes.
– **Many important science targets including craters and rock outcrops involve a significant risk of the rover getting immobilized** .

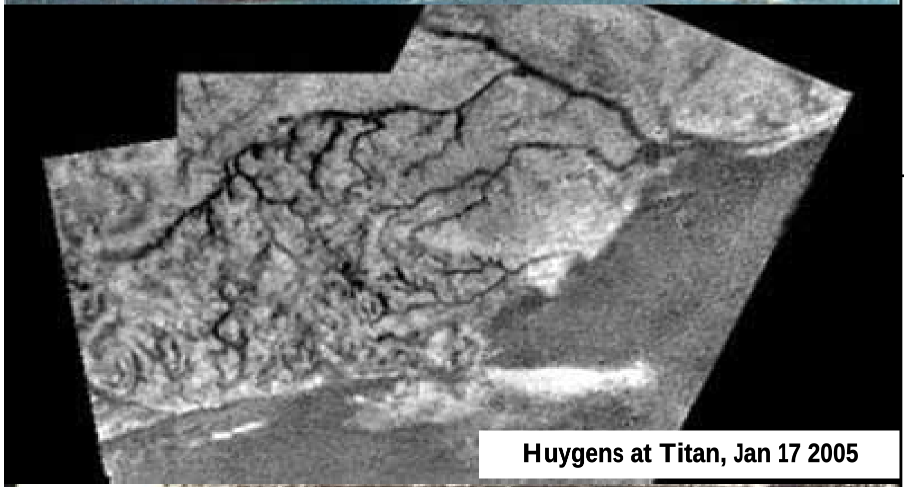
Titan

– Demonstration of key technologies to survive in the cold environment of Titan (FY03-05 R&TD).
– Initial test bed investigations of autonomy for Titan.
– **Not yet at a point that NASA could commit to a Titan in situ mission**.

Venus

– Capability to circumnavigate Venus by high latitude balloon (e.g. JPL VALOR proposal to the 2004 Discovery call)
– Near surface metal bellows balloon demonstrated in R&TD topic proposal in 2004
– **No other current NASA work on mobile near surface exploration of Venus**.

Planetary Mobility: Vision



Mars Surface Mobility

- ***Increase speed of travel*** by a factor of 20 and cover 100 km in three months
- ***Reduce power*** needed for locomotion by a factor of three.
- ***Traverse*** dunes, dust deposits, large boulders and steep slopes with equal facility
- ***Access rock outcrops*** above talus slopes at the angle of repose.

Titan Aerial Exploration

- ***Circumnavigate*** Titan and acquire 1000X the image data obtained by Huygens at high S/N
- ***Descend*** repeatedly to the surface of Titan to image fluvial and cryovolcanic features up close
- ***Acquire touch and go samples*** from selected targets on the Titan surface and perform *in situ* analysis.

Venus Aerial Exploration

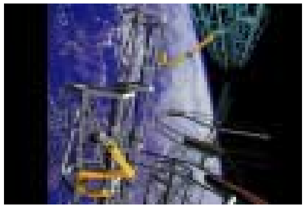
- ***Circumnavigate*** Venus and acquire 10,000 times the image data obtained by Venera 9-14
- ***Descend*** repeatedly to the surface of Venus and perform *in situ* analysis.
- ***Survive*** for several months in the Venus near surface environment .

Desired Space Robotics Capabilities

- **Solar System Exploration**
  - Autonomous mobility and access (surface, aerial, and sub-surface)
  - Autonomous instrument deployment (from landed and mobile platforms)
  - On-board autonomous science (with applications to opportunistic exploration)
  - Human-robotic field science (robotic scouts, assistants, telepresence, multi-robot cooperation)
  - Human-robot interaction (remote and on-site C^4I for mission planning, operations, monitoring)

- **Lunar & Planetary Habitation**
  - Site development (survey, excavation, initial construction, resource deployments)
  - Site maintenance (inspection, repair, assembly, materials transport & warehousing)
  - In situ resource production (robotic support to extraction, transport, manufacturing)
  - Field logistics and operations support (materials & equipment transport & warehousing)
  - Human-robot interaction (H/R task allocation, teleoperation, remote supervisory control, etc.

- **Robotics for In Space Operations**
  - Assembly (manipulation, preparation, connecting, self-deployment)
  - Inspection (structural, access, component/system failure detection)
  - Maintenance (staging, H/R interface rated manipulation, grapple dexterity)
  - Human-robot interaction (multi-agent teams, communication of intent, time delay compensation)



EXAMPLE: Capability Trends (1)

Required Capability	Current TRL	Now (TRL varies)	Figure of Merit In 2008 (TRL 6)	Long Term
Surface Mobility				
Command Cycles per Operation for Surface Mobile Exploration	3-9	Mobility: 10+ meters per command (MER) Manipulation: 3-4 sols per instrument placement (MER)	Mobility: 1 Kilometer per command Manipulation: 1 science measurement per command	Automated planning and sequencing of local area activities (science scripts, maintenance & logistics functions). Multi-target science sorties in one command.
Range of Operations (Planetary Surface)	3-9	> 1 kilometer linear path (MER)	>1000 Km^2 incl. use of aerial or multi-agent systems	Global coverage of science bodies through networked science assets
Access to Adverse and Rugged Terrain	4	VL 1 terrains, recent MER post-baseline ops on 30 deg. slopes	> VL2 terrains, vertical cliffs, cratered walls	Rove at will into densely featured and highly variable terrains at lunar and Mars gravity
Networked Robotic Systems (Surface)	2-4	Concept demos of shared payload transport (TRL 4)	Full scale terrestrial demo of power station / habitat deployment	Mix and match modularized hardware-software robotic assets for all basic surface H/R support and logistical functions
In-Space Mobile Dexterity				
Level of Dexterity	4-9	Teleoperatively Grapple Large (>1 m^3) ORUs (STS)	Human "bare hand" dexterity	Full body emulation of human assembly and repair skills by robotic anthropmorph
Range of Operations (In-Space Systems)	2-9	Fixed base (SRMS, SSRMS) operations; 100 meter linear track (MSS/SPDM)	1 Km^3 coverage by coordinated mobile manipulative systems	Robotically traverse complex space structures to perform planned and spontaneous inspection and servicing functions
Networked Robotic Systems (In-Space)	2-3	Cooperative transport and docking by free-flyers, air-table demo (TRL 3)	Dockable, modular multi-robot elements for assembly, servicing	Robots and crew freely and safely interact both physical-cooperative and symbolic command i/f levels

EXAMPLE: Capability Trends (2)

Subsurface & Aerial Access				
Autonomous Drilling/ Coring	3-6	Drilling 10-100's cm in penetrable rock, sand media; novel arm-mounted core extraction devices (TRL 3-4)	Drilling 10-20 meters in Mars analogs. Automated detection and mitigation of slip-stick conditions	Drilling 50-100 meters at Mars, drilling for resources as needed at Earth moon.
Icy Melt Exploration	2-5	Cryobotic access to uniform icy media (TRL 5)	Self powered and science instrumented cryobot earth analog experiment	Cryobotic exploration of Europan ice fields. Deep icy soil exploration of Mars high latitudes.
Aerial Access to Small Bodies	2-4	Powered aerobotic flight over terrain of interest (TRL 3-4)	Titan aerobot scenario demonstrated in full scale earth analog demo	Titan aerial exploration and possible drop-sonde and sampling.
Robotic Intelligence & H/R Interaction				
Planning & Monitoring Systems	3-5	Contingent Resources Planners; Local Spatial Planners (TRL 4-5)	Deliberative task planners for well structured assembly tasks; automated sequencing of basic science routines; integrated spatial-resource planners for long ranging traverse	Integrated planning and sequencing tools for ground operations of SSE robotic missions. High fidelity simulation of all aspects of planetary surface exploration.
Time Delay Control of Telerobotic Tasks (ground to orbit, from orbit to surface)	3-5	Teleoperative preview-predictive displays; shared compliance controls (TRL 3-5)	Teleprogrammed modes of remote control—the robot autonomously sequences local task behaviors / primitives	High dexterity operations over variable time delay from earth, orbit, and at field sites.

NASA Capabilities Assessment

Robotics

Paul S. Schenker and Christopher J. Culbert

Executive Summary: Through the new National Space Vision, NASA has received the charter and challenge of progressively staged human-robotic (H/R) exploration of the Solar System. This exploration encompasses the autonomous robotic precursors that will pave the way for safe and durable H/R presence at the Moon, Mars and beyond; it also encompasses the development of an orbital space infrastructure to support incremental, cost-effective deployment of both human and robotic assets deep into space. Robotics and its human interfaces thus address capability needs of future in-space assembly, maintenance, and servicing, also, operations on-and-near planetary bodies. The latter will entail significant elements of science, in situ resource identification and utilization—and ultimately—sustained human presence. The required capabilities include dexterous H/R work systems and highly agile robotic explorers. Relevant mission scenarios include construction and maintenance of complex space instruments/facilities, as well as long duration robotic access to new, hard-to-access science venues. Anticipated science returns include unprecedented spectral diversity and resolution of deep space astronomy via high orbit instrument construction, as well as breakthrough in situ science measurements at, and sample return from, diverse solar system surface, subsurface, and near-surface atmospheric sites. Critical sub-capabilities include richly detailed 3D machine perception, high precision robot dexterity, all terrain mobility with similar agility over man-made structures, deep subsurface access and sample acquisition, and the on-board intelligence to provide highly robust control in unstructured space environments, as well as fluid interaction between multiple human and robotic agents. Many requisite technologies are currently TRL 2-3; some system architectures are yet to be developed beyond lab floor prototypes. If NASA is to undertake a bold, productive path of exploration at Moon, Mars, and L1/L2 libration points in the forecasted 2015-2030 time-frame, then a strong program of mission/systems-driven and technology-focused R&D is needed, with large-scale verification & validation of new operational concepts in high-fidelity demonstrations.

Autonomous Aerial Exploration at Titan

Planetary and Lunar Rough Terrain Mobility

Robotic Work Crews at Moon and Mars

Robotic Maintenance and Repair

In-Space Large Structure Assembly

Co-orbital Free Flying Robotic Inspection

Capability Description: From an engineering perspective, robotics acts in place of, or operationally enhances and extends the presence of human mobility, manipulation, and intelligence in space. *Examples are*:

- Putting these functional capabilities where humans cannot yet go, to carry out human-like endeavors, e.g., Mars field geology
- Cooperatively placing capabilities where humans can go, due to task complexity, scale, duration, and human/robot system safety
- Extending human "reach" to the space frontier from Earth, e.g., through telepresence and telerobotic ground support
- Leveraging on-board automation and highly adaptive human-robot (H/R) interaction to robustly, safely perform complex operations in poorly modeled environments

From a science perspective, a more advanced robotics capability will enable breakthrough measurements and H/R construction of new in-space science instruments and facilities. *Examples are*:

- Instrument placements on planetary and lunar surfaces
- Mobility into high-risk, high-payoff sites such as Mars cratered slopes (e.g. the recent Endurance Crater discovery)
- Autonomous aerial survey of planetary and lunar bodies
- Subsurface drilling/melting into pristine science records
- H/R work crews that emplace science observatories/bases

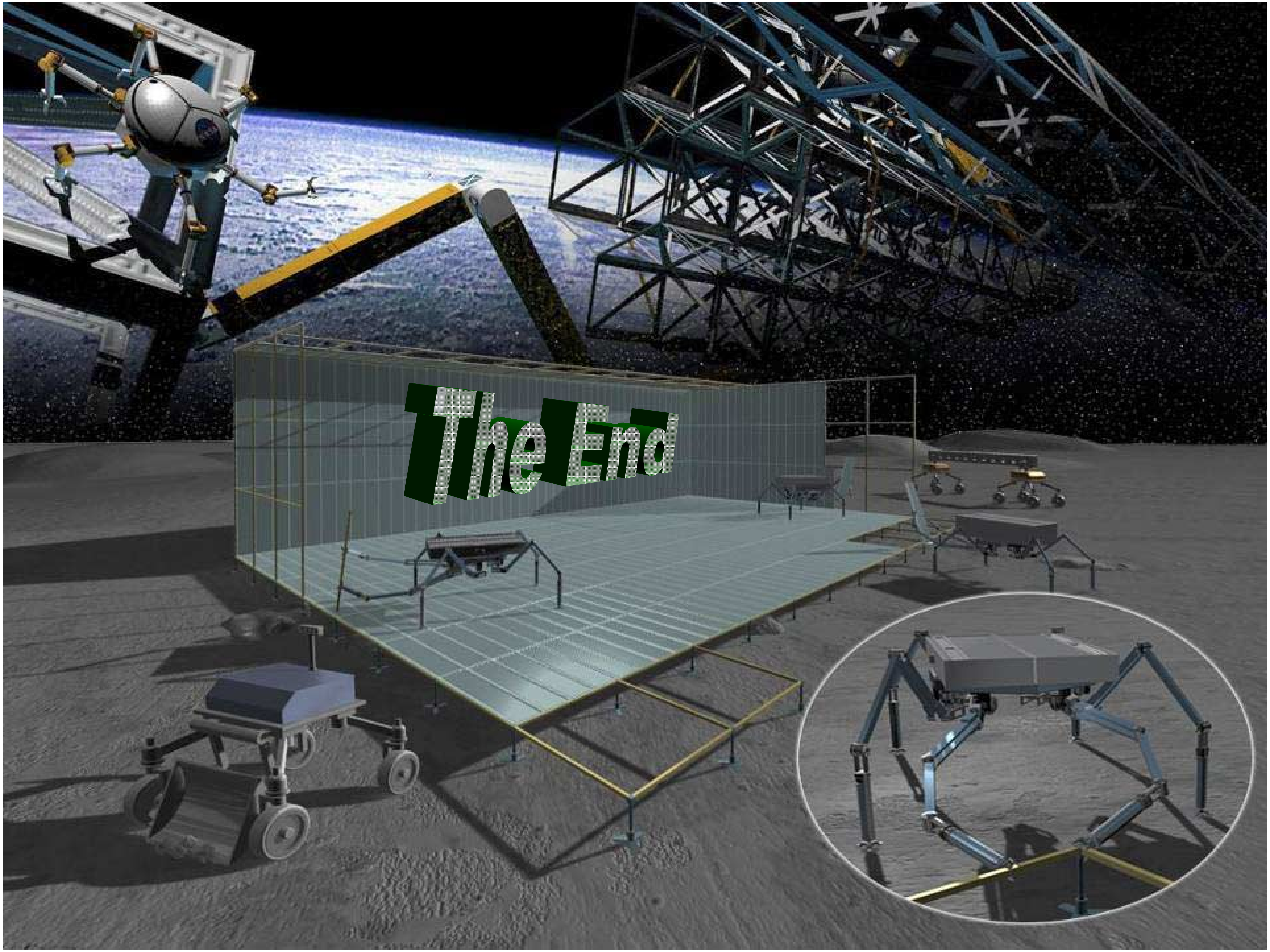
The above figure summarizes long term trends towards advancement of flight robotic capability for in-space and surface operations.

Capabilities Benefits:
(In-Space)—NASA design reference mission (DRM) architectures and related science facility concepts for large science platforms and human exploration point to complex assembly, inspection, and maintenance by

- **Whitepaper and supporting mission-based technology analyses**
- **Authors: <u>Paul S. Schenker</u> (JPL) and Christopher J. Culbert (JSC)**
- **System-integrative coverage of five NASA guideline capabilities**
  - **1. Machine perception**
  - **2. Robotic dexterity**
  - **3. Mobility**
  - **4. Subsurface Access / Sample Acquisition**
  - **5. Intelligence for Robots & Other Complex Systems***

Annotated References

1. ***The Future of Solar System Exploration***, 2003-2013, Ed. Mark V. Sykes, NRC Planetary Decadal Report, 2002 (http://www.aas.org/~dps/decadal). [The Decadal report is a 10 year perspective of SSE missions to the inner/outer planets and associated SS small bodies, incl. technology priorities to enable the larger mission sets]
2. **"Robots in Space": Special Issue of *Autonomous Robots* (Guest Editor, Paul S. Schenker)**, Vol. 14, Nos. 2/3, March/May, 2003. [Recent peer review reports on most aspects of space robotics (rovers, aerobots, new mission and operations concepts, telerobotic experiments and designs, etc.)]
3. ***The Vision for Space Exploration***, February 2004, National Aeronautics and Space Administration, Doc NP-2004-01-334-HQ, Washington, DC 20546. [Introductory vision/roadmap of ESMD/Code T]
4. Paul S. Schenker, et al., **"The expanding venue and persistence of planetary mobile robotic exploration—new technology concepts for Mars and beyond,"** SPIE Proc. 5267, *Intelligent Robots and Computer Vision XXI*: Algorithms, Techniques, and Active Vision (Eds., D. Casasent, E. Hall, and J. Roning), 27-31 October 2003, Providence, RI. Invited long paper. [Overview of technology needs to advance autonomous mobile robotic exploration for surface, aerial and subsurface venues, with reports on R&D work in progress and earth analog field demonstrations]
5. ***NASA Workshop on In-Space Construction and Maintenance of Complex Science Facilities***, University of Maryland, May 21-24, 2002 (Orgs., R. Moe and W. Doggett), http://iscworkshop.larc.nasa.gov/ [Survey of mission concepts and challenges for in-space robotics development and operations]
6. P. S. Schenker and G. T. McKee, **"Man-machine interaction in telerobotic systems and issues in the architecture of intelligent and cooperative control,"** Proc. of 10th 1995 *IEEE International Symposium on Intelligent Control — Workshop on Architectures for Semiotic Modeling and Situation Analysis in Large Complex Systems* (Editors: J. Albus, A. Meystel, D. Pospelov, and T. Reader), August, 1995, Monterey, California, ISBN: 1879789116. Electronic copy available on request (12 pages). [Overview of wide-ranging system concepts for telerobotic time-delay assembly-inspection-maintenance, incl. summary reports of new technologies and field demonstrations of same as regards H/R interaction at low-to-high levels of control abstraction. Surveys "intelligent control" interfaces. Extensive references]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